Israel C. Russell

GEOLOGY APPLIED TO MINING

A CONCISE SUMMARY OF THE CHIEF GEOLOGICAL PRINCIPLES, A KNOWLEDGE OF WHICH IS NECESSARY TO THE UNDERSTANDING AND PROPER EXPLOITATION OF ORE-DEPOSITS

FOR MINING MEN AND STUDENTS

BY

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PREFACE.

The writer was led to attempt the present volume througn the perception of how great a need there was, among mining men and students, of some work stating concisely those results of the science of geology which bear upon ore-deposits. No work of this type exists, so far as the writer is aware, in any language. The demand for such information is great among men of the classes referred to; yet in any of the available works on geology they find very little of that for which they are searching, combined with a great deal of that which, for the moment, is immaterial.

In preparing this work two points have been kept in mind; first, to make statements as clear as possible, considering the technical nature of the subject; and, second, to present the scientific facts accurately, and as fully as absolutely necessary. Simplicity of language has been constantly striven after, but it must be remembered that it is impossible to discuss any technical matter without using terms peculiar to it.

This book, as it goes forth, is far from meeting the author's perfect approval. It is a beginning, and it is

believed that the demand is sufficient to warrant its immediate publication. But it is the writer's purpose to work steadily at its improvement and elaboration.

So sincere is his wish to furnish the desired information to the large class for whom the book is intended, that he asks for private communications from readers, stating where they have not found the writing clear enough, or asking information on questions not contained in this book. Such suggestions will be a valuable aid to future enlargement and revision.

Although the writer addresses men who have had little to do with geology as a science, or with the theory of that particular branch of geology with which the book deals—namely, the study of ore-deposits—yet, before developing his subject, he has deemed it necessary to anticipate a little. With this purpose the first chapter has been inserted. For a correct understanding of the science of ore-deposits, and how the principles of geology may be practically applied to economic advantage in finding and exploiting ore-bodies, it is necessary, first of all, to have some ideas of what ore-bodies are, and how they have formed. The study of the processes of ore deposition has long been in a state of slow growth; within the past twenty years, however, it has been more rapid and steady than heretofore, and the writer feels justified in laying down certain principles.

Suggestions and criticisms of the most helpful nature in regard to this work have been made by friends, who have read portions of the rough draft of the manuscript. For such aid grateful acknowledgment is due to Messrs.

T. Wayland Vaughan, A. H. Brooks, and Waldemar Lindgren, of the United States Geological Survey. Especial thanks are due to Mr. T. A. Rickard, Editor of the *Engineering and Mining Journal*, who carefully went over the manuscript and made such trenchant suggestions as to its revision that the general presentation was greatly altered and improved thereby.

J. E. Spurr.

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CHAPTER I.

THE PROCESSES OF ORE DEPOSITION.

METAMORPHISM, OR CHANGES IN THE EARTH'S CRUST.

THE ORIGIN OF METAMORPHIC ROCKS.

Is the earth's surface stable?

The seemingly stable crust of our earth undergoes slow but stupendous alterations. In the course of our brief lifetime we may not notice them; but, if we do, we marvel at them. Such things as a river that has shifted its course, a harbor that becomes choked with sand, or a mud island that is washed away by the waves, interest us strongly. Yet the researches of geology show that, during the long succession of centuries, rivers which run from the uplands to the sea may entirely remove mountains and spread them out as sediments upon the ocean floor. In the course of time these deposits may be lifted above the sea again to form new land; for the crust of the earth is not quiet, but is forever heaving up and down, expanding, contracting, bending and breaking, converting sea-bottoms into dry land, sinking mountains into the sea, and crumpling plains into mountains. All this goes on with such undemon-

strative slowness that those who live on the earth are hardly made aware of these changes and are rarely disturbed by them.

Example: Modern history records upward and downward movements of the land at various points. It has lately been ascertained that the whole region of the Great Lakes is undergoing a slow tilting to the south-southwest. Measurements, extending over a number of years, of the distances between certain marks and the level of the lakes render it probable that the region is being lifted on one side or depressed on the other, and that the rate of change is such that the two ends of a line 100 miles long and lying in a south-southwest direction are relatively displaced four-tenths of a foot in 100 years. The waters of each lake are rising on the southern and western shores, or falling on the northern and eastern shores, or both. At Toledo and Sandusky, the water advances 8 or 9 inches in depth in a century. A tract of land near Sandusky on which hay was made in 1828 is now permanently under water. In 3,500 years the Falls of Niagara will cease to flow, as a consequence of this movement.*

How may sedimentary rocks become metamorphic?

Regions which were once deeply buried may become part of the surface by the removal of the overlying mass; and study of the rock thus revealed gives an idea of what goes on in the depths of the earth. Among the lessons thus learned is the following: When sediments have accumulated (as they may in the course of ages), to a depth of several miles, the lower layers may be affected by the weight of

* G. K. Gilbert, 18th Annual Report United States Geological Survey, Part II, pp. 601-645.

those above, by the internal heat of the earth and other causes, so that chemical changes take place. The materials begin to recrystallize, new minerals grow from the débris of those in the sediments; and finally the rock becomes quite different in appearance.

Sometimes we find such a rock with the marks of its sedimentary origin still visible. Other rocks may be so perfectly recrystallized that there is no direct evidence in their structure that they ever were sediments, and we can only determine this point in roundabout ways, as by tracing the much altered rock into some less altered portion. Such rocks are *metamorphic;* and they are chiefly divided into *schist* and *gneiss.*

Example: In the northwest highlands of Scotland, on Ben More and on Sgonnan More, movements in Cambrian conglomerates, sandstones and shales have produced extraordinary changes. The conglomerate in its unaltered form is composed of rounded pebbles in a loose, gritty matrix. Where subjected to movement the softer pebbles have been crushed, flattened and elongated in the direction of movement. In some cases they have been drawn out to such an extent as to form thin lenticular bands of mica or hornblende-schist, flowing around the harder pebbles of quartz. The original gritty matrix has been converted into a fine micaceous or chloritic schist. Were it not for the presence of the crushed schistose pebbles it would probably be impossible to tell that this schist had a sedimentary origin.*

* B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman, and H. M. Cadell, *Quarterly Journal*, Geological Society, Vol. XLIV, pp. 431-432.

How are igneous rocks formed?

The metamorphic rocks are related to another class of crystalline rocks—the true igneous rocks. The igneous rock has crystallized from a molten condition. At the surface the formation of igneous rock is illustrated by lavas, but such rocks are formed on a grander scale beneath the surface. An igneous rock has generally a fairly constant texture, and is composed throughout of the same minerals, which are often about the same size, and lie in different attitudes. These characteristics arise from the circumstances that the mass has been fluid before cooling, so that all parts come to have about the same composition; and since all parts have cooled under nearly the same conditions, the resulting minerals and structure are the same.

Why are metamorphic rocks often banded?

A true metamorphic rock has not been really fluid, in the generally accepted sense of that word. At the most, the effect of pressure and heat have made it slightly plastic, so that it has yielded and slipped a very little. Therefore, when it recrystallized, the materials did not move far in the rock. If there were in the original sediments successive layers of different nature, (such as dark ferruginous mud beneath clean quartz sand), the recrystallized rock will often preserve the banding; the mud will appear as a dark layer of crystalline ferruginous minerals and the sand bed will be represented by crystalline quartz.

Banded structure in metamorphic rocks may also be produced by more active crystallization along slipping planes than in the rest of the rock.

May a metamorphic rock assume the characters of an igneous rock?

The conditions which make a mass *plastic* and those which make it *fluid* are not sharply separated. A rock undergoing metamorphosis may become so plastic and so thoroughly recrystallized that the result will be the same as if the rock had slowly cooled from a molten state. Some igneous rocks are known to have been thus formed, by slow metamorphism, from sediments. When we can prove the origin of such rocks, we often prefix the term metamorphic to them—thus, metamorphic granite—but often we cannot tell whether a granite is metamorphic or igneous, for the characters are alike.

May an igneous rock assume the characters of a metamorphic rock?

An igneous rock may, by becoming subject to conditions of long-continued slight plasticity and pressure, acquire the characters of a true metamorphic rock. A slight movement takes place, generally along close-set parallel planes, and here an active recrystallization and a re-arrangement of the minerals occur, resulting in a banded structure. The rock may lose all the traces of its essentially igneous character, and become a gneiss or schist, indistinguishable from one that has formed by the alteration of sediments.

Example: The crystalline schists and gneisses of the Malvern Hills, in England, have been formed by the meta-

morphism of igneous rocks. Shearing has taken place in bands of varying breadth situated at irregular intervals. The gneissic structure usually shades off on each side of the zone into ordinary igneous masses (diorite, granite, etc.), and within the zone itself the metamorphism varies in intensity. Proofs of mechanical forces resulting in shearing are numerous. Hornblende crystals are drawn out into ribbons, and feldspars are bent and broken. Frequently black mica is formed along the shear-planes, so that the rock splits into thin leaves whose surfaces glisten with mica, while the interior may be dioritic. The chief mineral changes are the recrystallization of feldspar, and the production of biotite, muscovite, quartz and actinolite.*

Transformation of Igneous and Metamorphic Rocks into Sedimentary Rocks.

Can igneous and metamorphic rocks be changed back to sedimentary ones?

The earth's surface consists in part of igneous and metamorphic rocks. These rocks are attacked by the rain, the sun and the frost; they are broken up by snow, by ice, by glaciers, by landslides and by the roots of plants; and the débris is carried down the hillsides into the valleys, and along small streams into large ones, till it is emptied as sand or mud into the sea, to become slowly solidified into sedimentary rocks. The igneous or the metamorphic rock may originally have been derived by recrystallization from

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*C. Calloway, *Quarterly Journal*, Geological Society, Vol. XLV, p. 475.

a sedimentary one, so that the materials have undergone a complete circle or *cycle* of change.

Can we find a beginning in the cycles of change?

So vast has been the period of time, during which such processes have been going on, that there is scarcely any rock of which we can say with certainty that it has not been derived from another, of different nature. Still, we can rarely be sure that an igneous rock *has* thus been originated, and it is probable that many such rocks have never been anything else, but have crystallized directly from the molten interior. And since we can always trace the sedimentary and the metamorphic rocks back into the igneous originals—if we go back far enough—we may regard the igneous rock as the beginning of the cycle.

Special Metamorphic Processes Connected with Ores.

Has the consideration of rock-changes a direct bearing upon ore-deposits?

A rock is an aggregate of minerals; and with the transformation of the rock the minerals undergo change. The commonest rock-forming minerals are quartz, feldspar, mica, hornblende and augite, these being made up of the elements chiefly represented in the earth's crust. The rarer elements are also scattered through the rocks, and occur in more or less abundant minerals. Certain of these minerals, notably the heavy metals, have been put by man to use in the arts, and it is especially with these that the science of ore-deposits is concerned.

What are the limits of the study of ore-deposits?

Accurately speaking, the science of economic geology would embrace the study of the distribution of *all* the elements, for practically all have some use; but it is the rarer ones that it takes most intelligence and energy to find and extract. For example, the most common of all the elements (except oxygen) is silicon, which in the form of sand is of great economic value. But it is so easy to find and dig sand that small attention is paid to this element in the study of economic geology. When we come to the next commonest element, however,—a metal, aluminum—we begin to pay closer attention. Clays, which are impure silicates of aluminum, are sought after and studied for pottery, porcelain, brick, tile, cement, etc.; and for the manufacture of the pure metal and many other purposes we seek and investigate deposits of highly aluminiferous minerals, such as bauxite and cryolite, corundum and emery, and natural alum. Arriving at the next commonest element—iron—we are fully in the domain of mining; and so on down the list—calcium, magnesium, potassium, sodium, titanium, carbon, phosphorous, manganese, sulphur, barium, chromium, nickel, etc. The statement resolves itself into this—that man finds artificial uses for all the elements, and economic geology busies itself especially with those which are most highly prized, and which are difficult to find in a sufficient degree of concentration, or in the proper combination with other elements, forming minerals which possess valuable properties. Especially does it require study and effort to produce in quantities the rarer

elements, notably the less common of the heavy metals. On that account the science in general, and this book in particular, will deal principally with these metals.

The rarer metals—tin, lead, zinc, silver, antimony, gold, etc.—occur in small quantities nearly everywhere in the earth's crust—in rocks, in both fresh and salt surface water, in underground water, and even in plants and in animals. It requires rather exceptional conditions, however, to produce a mass containing such a proportion of these as to render it profitable to make it the basis of mining operations.

PROCESSES OF ORE-CONCENTRATION.

In what way does concentration of valuable elements take place?

We may conveniently divide the underground processes of concentration into two classes—those which take place within igneous rocks while they are still wholly or partially molten or during their cooling period, and those which are brought about chiefly through the action of percolating waters in solid rocks.

Concentration Directly from Igneous Rocks, While Molten or Cooling.

Theory of Direct Concentration of the Basic Constituents During a State of Chiefly Igneous Fluidity of the Rock.

How may concentration take place in molten masses?

Petrographers have advanced the theory that in molten masses the different elements tend to segregate. In this way

it has been supposed that different rocks, such as granite and diabase, may separate out of the same molten mass. Granite contains much silica, diabase much magnesia and iron.

Example: In west Cornwall the tin and copper veins are associated with intrusive igneous rocks. These are granites, greenstones, etc. In some cases it is found that the granite becomes less silicious toward the edges, a condition which is supposed to have been brought about by segregation while still molten. This granite is cut through by more silicious dikes, which, however, are evidently closely related to the granite. The greenstones, which are in smaller quantity, are altered basalts and gabbros, and generally occur near the margins of the granite intrusions, though not in the granite.

This geographical connection and the order of intrusion, as worked out for the different rocks, favor the hypothesis that the silicious and the basic rocks have originated by the splitting up of an earlier molten mass of intermediate composition.*

With the iron of the basic rocks are generally small amounts of some of the less common metals, in relatively greater quantities than in the light-colored silicious rocks. The metals are apt to be more abundant in some portions of the dark heavy rocks than in others. Thus there may be formed masses which are chiefly made up of metallic minerals. By such a process of magmatic segregation some iron deposits, some chromite (chrome iron) deposits, some of nickel, etc., have been supposed to be formed.

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* J. B. Hill, *Transactions* Royal Society, Cornwall, Vol. XII, Part VII, p. 579.

Example: In Lancaster county, Pennsylvania, the Gap mine has, as chief metallic mineral, magnetic iron pyrite (pyrrhotite), which contains sufficient nickel to render it valuable as an ore of that metal. The ore occurs at the contact of a lens-shaped mass of dark basic hornblende-rock (amphibolite), which has been intruded (thrust up) into mica-schists. This hornblende-rock is considerably altered and when fresh had a different mineral composition, being probably one of the very basic* rocks *gabbro* or *peridotite.*† It is believed by J. F. Kemp‡ that the pyrrhotite which occurs in the outer rim of this basic intrusion is one of the original minerals, crystallized out of the cooling rock and segregated along the contact. (See Fig. 1).

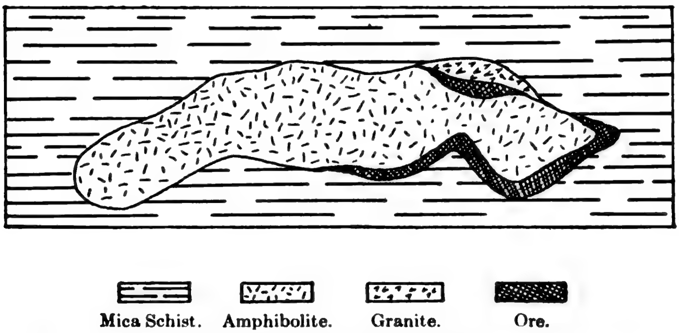

Fig. 1. Generalized Map of Gap Mine, Lancaster, Pa., after J. F. Kemp.

Is this concentration in molten masses a very common and important process?

It is held by many that not infrequently metals are so highly concentrated in this way as to actually form ore-deposits; and that when this is not the case, the process may

* The term basic is applied to igneous rocks rich in dark-colored heavy minerals containing iron, and poor or wanting in quartz.

† For definitions of these rocks see pp. 86, 90.

‡ "Ore-Deposits of the United States," p. 434.

still be important, in producing rocks which carry relatively large amounts of the metals, though in a scattered condition. These scattered metals, through the agency of further concentration, (by circulating waters, for example), might give rise to ore-bodies; while the same agencies, acting on rocks, poor or wanting in the metals, would not contribute in that way.

Example: At Riddle's, Douglas county, Oregon, there is a very basic rock, peridotite, made up of the minerals pyroxene and olivine. The olivine contains a small percentage of nickel, analysis having shown 0.26 per cent of oxide of nickel. This rock has become thoroughly decomposed, and has altered to serpentine. During the alteration of the olivine, the nickel has separated out. Surface waters, percolating through the rocks within the zone of rock decay, have taken the nickel into solution, and have precipitated it as a coating on the walls of cracks and in small veins. From this method of formation it has resulted that the ores are richest at the outcrop, and diminish lower down, till, on passing below the zone of surface decay, they disappear.* In this case the ores have been concentrated in their present form by surface waters, although in their original condition in the fresh rock they were too sparsely scattered to be noticeable; yet had it not been that there was within the molten rock, previous to cooling, an unusual proportion of nickel, the material would not have been at hand for the waters to work upon, and no ore-deposits would have been possible.

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* Clarke and Diller. *American Journal of Science.* Series iii, Vol. XXXV, p. 1483.

Theory of Concentration of the Silicious and Other Constituents, in a State of Aqueo-Igneous Fluidity.

It is not so much dry heat which renders molten igneous rocks fluid, as it is water combined with heat. In the different kinds of molten igneous rocks, water is present in different proportions. In general, the more silicious a molten rock is, the more water does it contain. The relative order in which the different minerals crystallize in granite, for example, cannot be explained by dry heat, but only by admitting that the materials from which the mineral formed were in a state of partial solution in water. It is held by some writers that ore-deposits may originate, under the combined influence of water and heat, in the silicious igneous rocks.

How is this process supposed to operate?

It has been found in the field that granites may pass gradually into more silicious rocks composed of quartz and feldspar, and that these may pass into quartz veins. It has been held by some writers that such quartz veins have a genetic connection with the granite. Their formation has been explained by applying the theory of magmatic segregation, as follows:*

The silicious rocks, such as the granites, may originate by differentiation from a more basic magma. With the further development of this process, quartz-feldspar rocks may be formed; and, when the silica separates out from the magma in a nearly pure state, quartz veins may result.

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*J. E. Spurr. "Igneous Rocks as Related to Occurrence of Ores." *Transactions* American Institute Mining Engineers, Feb. and May, 1902, p. 21.

Example: There are numerous veins and large masses of quartz throughout the district of Omeo, Australia, in schists or granular igneous rocks. The quartz is in places milky in color, in others clear. In addition to the quartz veins there are others of the same class which contain tourmaline or feldspar, or muscovite (mica), or two or all of these together in varying proportions, so that veins may be extremely quartzose with but a small proportion of other minerals, or may be so charged with them as to become a variety of pegmatite. Study of the veins composed of quartz alone, or quartz and tourmaline, shows that the quartz has broken the tourmaline crystals, and penetrated every crevice. The supposition that the quartz may have been gradually deposited from solution around the tourmaline crystals till the fissure was completely filled is negatived by the observation that the tourmaline is not attached to the walls of the veins, but "floats" free in the quartz. These facts are explained by the author on the hypothesis that the veins represent the residual silica of the granitic rocks of the region, after the other minerals had crystallized out, and that this residuum was squeezed out while in a plastic state into every adjoining crevice.

These veins occur in a rich gold-quartz region; nevertheless, the author considers that the auriferous quartz veins have had another origin.*

Since it is probable that the amount of water in the igneous rocks increases in general with the increasing content of silica, the end product of differentiation, from which the quartz veins are crystallized, may be little more than highly heated and compressed waters, heavily charged with silica

*A. W. Howitt, *Transactions* Royal Society Victoria, Vol. XXIII, pp. 152–154.

in solution. Besides silica, other residual materials, left over from the magma, may be present, among them gold; so that the resulting quartz veins may be auriferous. Such veins might have the same appearance as those formed by ordinary underground waters.

Example: In the gold-bearing district of Silver Peak, Nevada, are found quartz veins which pass gradually into silicious granitic dikes, and seem to represent the silicious extreme of segregation or differentiation of the granite. Such veins usually contain a little feldspar and white mica, while others to which a similar origin may be assigned, contain none. Assays for gold and silver were made from two of these veins. One contained 0.03 oz. gold and 0.13 oz. silver, the other none.*

Extraction of Silicious and Other Constituents, in Solution, in Waters Expelled from Cooling Rocks, and Deposition in Foreign Rocks.

Are waters and vapors active when an igneous rock is in process of cooling?

When an igneous rock begins to cool and harden, much water, which has been a part of the molten material but cannot form part of the rock, is pressed out. If the igneous rock is at the surface, like a lava, this water, which is highly heated, passes off in copious and long-lasting clouds of steam. In the case of necks of molten rock, which feed volcanoes, and of other bodies which have forced their

* H. W. Turner. Report for United States Geological Survey. (Unpublished MSS.)

way up from the depths, through other rocks, but have not succeeded in getting to the surface, the water is forced into the adjoining rocks and, being under pressure, may be either in liquid or vaporous form.

These waters are highly charged with various strong vapors, and both water and vapors carry in solution much mineral matter, among which may be the metals. It is believed by many geologists that this mineral matter is deposited while the solutions are in process of circulation through the rocks, and, further, that the metals may be concentrated so as to form ore-deposits. Certain ore-bodies found at the contact of an igneous rock with another rock have been described as having this origin. Such occurrences are termed contact-metamorphic ore-deposits.

The commonest kind of contact metamorphic ore-deposit is usually held to occur at the very contact of the igneous rock. But contact metamorphism in general may extend much further, forming an altered zone a mile or more broad. Anywhere within this zone deposits of metallic minerals, with the characteristics of contact-metamorphic ore-deposits, may be found.

Example: The Dolcoath mine, in the Elkhorn mining district, Montana,* lies in limestone, at a distance of over half a mile from the granite, which has chiefly occasioned the metamorphism of the district. Through this metamorphism the limestones have been recrystallized to marble, the sandstones have become quartzites, the sandy and limy shales are largely recrystallized to new minerals such as

*W. H. Weed, 22d Annual Report United States Geological Survey, Part II, p. 506.

pyroxene, garnet, epidote, etc. The ore-bearing stratum of the mine was originally a bed of impure limestone, which has been metamorphosed to garnet and pyroxene, with spots of calcite. Associated with these gangue-minerals are sulphide and telluride of bismuth, containing gold.

Ore-Deposits formed Chiefly by Vapors.

May some ore-concentrations be accomplished chiefly by vapors?

Tin-veins are held by many writers to be usually formed in this way. They are ordinarily confined to granite. The explanation usually offered is that when the granite cools, it shrinks, and crevices begin to open. Water escaping from the hardening rock rises along these rents in the form of vapor, and is accompanied by other especially powerful vapors, such as chlorine and fluorine. The vapors may carry tin and other mineral matters, which they may deposit in the rents or in the porous walls, and thus concentrate them sufficiently to make an ore-deposit.

Are tin-veins alone due to he action of vapors?

Others metals are known to be deposited by escaping vapors. They have been found encrusting the mouths of steam-jets (*fumaroles*) in lavas. Cinnabar, the ore of mercury, and realgar, an ore of arsenic, as well as hematite, an ore of iron, with copper and lead chlorides, are among the metallic minerals which have been thus deposited at Vesuvius. It is likely that some workable cinnabar deposits and even some of the other metals may have been formed underground by vapors alone.

The Origin of Certain Hot Springs.

What becomes of the water expelled from molten rock in cooling, besides that which passes off in vapors at the surface?

We have seen that when intensely heated rock cools at the surface, great quantities of the expelled waters pass off as clouds of steam. As the crust slowly hardens, and the congealing molten rock becomes further away from the surface, the escaping waters will become cooler in their passage upward. A stage will finally be reached when they will not entirely flash into steam on emerging, but will remain liquid, though boiling and sending off a great deal of steam. They will, in fact, emerge as hot springs, and it is probable that the change from steam-jets (fumaroles) to hot springs is the normal process of cooling volcanoes. As the cooling progresses, these springs will lose in temperature, volume and pressure, until finally they will in many cases become extinct.

The water which is given off at the contact of an intrusive mass of igneous rock, and which is frequently so active in producing contact-metamorphism, must also exist after it has accomplished these changes. We may suppose that if there are any channels, such as are afforded by fissures or faults, this water may find its way upward, and perhaps even reach the surface.*

May such waters produce ore-deposits?

We have seen in considering contact-metamorphic ore-

*Springs having this origin may be called (following Professor Suess, of Vienna,) *juvenile* springs, the term referring to the recent birth of the water from the molten rock.

deposits that compressed vapors and waters expelled from solidifying igneous bodies are supposed to produce ores in the adjacent intruded rocks; and that the vapors that escape from volcanoes often deposit metallic minerals. Therefore it may well be, also, that the hot waters which succeed the vapors in the cooling of volcanic rock are efficacious in concentrating ores. Ascending hot waters are generally conceded to be the most powerful agents of mineralization, and those hot waters which have the origin above described should be especially active, for in addition to their dissolving power, exerted on rocks which they traverse, they may contain metals expelled in solution in them from the crystallizing rocks from which they have emanated.

Concentration by Underground Waters in General.

Does concentration cease when the rock is cold?

The work of concentration does not cease with the complete cooling and hardening of the igneous rock. Rainwater, falling upon the surface, is, in part, carried off in rivulets and streams to the ocean; but probably the greater part sinks below the surface. The underground water circulates chiefly through natural channels, such as are offered by any fissure or porous zone; but it also possesses the power of working itself very slowly through most solid rocks. From the moment these waters touch the surface they dissolve substances from the rocks and precipitate them again at other points. This work they do continuously, and thus as far down as they penetrate there is a

constant shifting of material. From the affinity of like minerals for each other, this shifting results in concentration; and where metallic minerals are concentrated, ore-deposits are formed.

These waters, after sinking deeply, or nearing some body of hot igneous rock, may be supposed to become heated, and would then be still more powerful than before. They may take up the unfinished work of concentration left by the cooling processes of igneous rocks, and carry it to a successful finish in the form of a workable body of ore; or they may concentrate the metals sparsely scattered through igneous, sedimentary or metamorphic rocks.

Is there any universal final stage of concentration?

These processes of concentration are never at an end. With changing currents of water the ores are redissolved and reprecipitated, changing their position and proportion. An ore-body formed by deep underground waters may, in consequence of the slow wearing away of the surface, finally come to be exposed, or "outcrop." Then the shallow underground waters may either make the ore poorer, or make it richer, by dissolving and reprecipitating.

Even after a mine is opened, the work goes on, and metals are often deposited on the walls of drifts, or encrust tools which may be left in old workings.

Concentration by Surface Waters.

Surface waters have a twofold effect—chemical and mechanical.

How do surface waters act mechanically so as to concentrate ores?

In large bodies of surface waters, as in streams or on the shores of the ocean, the sediments, or finely ground materials worn from the rocks, become arranged according to the relative weight and size, by the operation of the same laws as those by which ores are concentrated in mills. In a current of water the heaviest minerals sink first, and so are separated from the lighter material, which is carried on. When the sediment, which is thus transported by water, has been taken from a decomposing rock containing valuable minerals, such as gold, platinum and tin, these heavy minerals become concentrated at certain points where the current is too weak to carry them further, but is too strong to allow most of the other materials to drop.

How do surface waters act chemically in concentrating ores?

There is no stream, however clear, which does not contain dissolved mineral matter. This material may, on occasion, be precipitated in large quantities, making sometimes a deposit of economic value.

RELATIVE WORK OF UNDERGROUND AND OF SURFACE WATERS.

How do the mechanical and chemical activities of underground waters compare with those of surface waters?

Underground waters move slowly through the rocks, often occupying every available space, no matter how minute. Ordinarily, however, they cannot unite into bodies of large volume like rivers and lakes, for they cannot

find underground spaces large enough. This difference makes their mechanical power practically nothing—for they cannot carry mineral particles with them by the force of their motion. But their chemical work is vastly more important, for two chief reasons. The first is the greater field of the underground waters, which work up and down, and through and through a thick belt of rocks containing small quantities of metals, while the surface waters only skim the top of this belt. The second reason is that, by virtue of the pressure and heat which the underground waters frequently attain, their power of solution, and hence of concentration, is correspondingly increased.

The Mode of Ore Deposition.

Are ore-bodies formed by upward, downward, or laterally moving waters?

Underground waters move sometimes upward, sometimes downward, sometimes sidewise; and, whatever their direction, they have the power to dissolve and reprecipitate mineral matter and hence to bring about concentrations of ore. The ore-deposit formed by descending waters may often be with difficulty distinguished from one formed by ascending waters. Yet from the fact that heated waters naturally rise, and that they are more capable of solution than cold ones, it is probable that the most important single class of ore-deposits has been formed by them.

How are ores deposited by waters in rocks?

Following the question as to what kind of underground water has accomplished ore-deposition, the next inquiry

concerns the manner in which the ores in solution are deposited in the rocks. The theories advanced by learned men have perhaps exhausted all the possibilities of the imagination as well as of reason. Three chief theories, now each of them proved facts, have been most successful in standing the test of time. These are the theories of *substitution* or replacement, of *cavity-filling*, and of *impregnation* or the filling of interstices (interstitial filling).

Study shows that not one process is represented in the average ore-body, but many. In most of them, one may find excellent examples of the work of each of the three processes above mentioned, and, even in a single hand-specimen of ore, the same multiplicity of origin may be displayed; although in general one process is chiefly active in forming a certain ore deposit, and another process in a second. Thus we have many typical replacement deposits (among them many lead-silver ore-bodies in limestones) and many typical fissure veins (where an open rift or fissure has been filled by ore); yet, in the replacement deposit, one may often find instances of fissure-filling; and, in the fissure vein, examples of replacement.

CHAPTER II.

THE STUDY OF THE ARRANGEMENT OF STRATIFIED ROCKS AS APPLIED TO MINING.

THE FORMATION OF STRATIFIED ROCKS.

Formation of Sediments by Mechanical Agencies.

How are sediments formed by mechanical agencies?

Rivers come down from their sources laden with mud and dragging along pebbles on their bottoms; on reaching the sea the coarse gravel is usually deposited near the mouths of the rivers, while the finer material is carried further on. Along the shore the waves attack the cliffs, undermine them and finally cause them to break off, and in this way new supplies of rock are produced, to be ground into sand and mud by the churning of the surf. The tides and currents sweep the material far out to sea or along the coast.

In lakes, the material brought down by the streams likewise settles on the bottom.

Rivers work slowly to either side in their valleys; they nearly always have a winding course, and at every curve the current may be seen cutting under and removing the bank on the concave side, and depositing sediment on the opposite or convex margin, so as to produce a spit or bar.

The result of many centuries of this cutting and rebuilding is that the stream widens the valley, and that the valley becomes covered with gravel and sand, which has been washed, worked over, and abandoned by the stream.

FORMATION OF SEDIMENTS BY CHEMICAL AGENCIES.

Are all sediments formed by broken and ground-up rock?

Besides the material which surface waters carry in suspension, as mud, sand, or gravel, they contain substances in solution. In limestone districts, for example, the waters contain lime, and cooking utensils and boilers in which such water is used become coated with this material, deposited from the evaporating liquid. In nature this lime is deposited similarly and on a large scale. In shallow lakes and land-locked seas the water brought down by streams from limestone regions may, after standing and evaporating, precipitate lime on the bottom of the lake. This deposit is generally lime carbonate (limestone); sometimes it is lime sulphate (gypsum).

Is lime the only material chemically precipitated as sediment in such cases?

Besides lime, other minerals are chemically precipitated in ocean and lake waters, especially silica, but all in a far less degree.

FORMATION OF SEDIMENTS BY ORGANIC AGENCIES.

In lakes, seas and in the ocean, there live myriads of animals that form their hard parts by extracting it from the sea water. They absorb the mineral that is in solution and

build it into their shells. It is generally lime that they absorb and their shells are of lime carbonate. Such are all of our ordinary shell-fish, as well as corals and a myriad of others, familiar and unfamiliar. It is a familiar story how corals live and die, leaving their limy shells behind; how new animals build upon the skeletons of their ancestors, and so on, till great masses are produced. In the same way other shell-bearing marine animals may furnish material which, little by little, accumulates to great thickness. There are thick strata which consist almost entirely of oyster shells, and so on.

Transformation of Sediments to Hard Rocks.

How do these sediments become rocks and dry land?

By the warping and folding of the earth's crust, brought about slowly during centuries of centuries, sediments are brought out of the water and become part of the land. They ordinarily harden with time. They may come to occupy any position; it is as common to find sedimentary rocks on the top of mountains as in the low plains.

THE PHYSICAL CHARACTERS OF SEDIMENTARY ROCKS.

How can one distinguish sedimentary rocks from metamorphic or igneous rocks?

Sedimentary rocks are distinguished from metamorphic or igneous rocks by their physical characters. They are often plainly *fragmental*—that is, they are made up of broken, often waterworn fragments, large or small; or,

like limestones, they are of a composition unknown in any other than sediments. Fossils are almost infallible evidences of the sedimentary origin of the rock which contains them.

What is stratification or bedding?

This is another feature of sedimentary rocks. When we cut a pit in the sand on the sea-shore, we see that the material is deposited in layers, one layer, for instance, being sand and another pebbles; or, if all the layers are of sand, there is some slight difference, as of color.

This arrangement of successive layers is called bedding or stratification. It arises from the fact that the material laid down in water will ordinarily vary during successive periods. All sedimentary rocks show this characteristic more or less plainly. Each separate layer is called a bed or stratum. Some rocks show distinct beds only a few inches or even a fraction of an inch thick; these rocks have been deposited under changing conditions—near the shore of an ocean, for example, where the varying currents brought about supplies of different kinds of detritus. In other rocks the beds are thicker, and in some they may extend through a thickness of many feet with a scarcely perceptible stratification.

What is meant by the word 'formation' as used in reference to rocks?

The term *formation* is generally used by miners as a name for any particular body of rock—thus a limestone formation, etc. This use of the word is, in the writer's

opinion, proper. Geologists use the word with a different technical meaning, limiting its use in various ways. Where rocks of different kinds and of different ages lie one over the other, each belt, marked by certain constant characteristics, is called a formation. In this sense a formation may be only a few feet or thousands of feet thick. Geologists often give a distinctive name to each formation, for the sake of identifying it in description or in mapping.

THE CHIEF KINDS OF SEDIMENTARY ROCKS, THEIR ORIGIN AND CHARACTERISTICS.

What are the ordinary sedimentary or stratified rocks?

The ordinary sedimentary rocks are conglomerate, grit, sandstone, quartzite, shale, slate, limestone, marble and dolomite.

What are conglomerates, and what is their origin?

Beds of pebbles, when cemented together, form conglomerate. They can be distinguished by the stratification and the rounded pebbles.

What is a grit?

A coarse and impure sand, when hardened, is called a grit.

What is a sandstone, and how does it originate?

When sand hardens so that the grains stick firmly together it becomes a sandstone. Sandstone is of all colors, white or red being the most frequent. In pure

sandstone the component grains are entirely of quartz; these rounded grains can usually be seen with the naked eye. Sandstones are porous, for between the grains there are tiny spaces or interstices.

How does quartzite originate?

The underground waters which usually permeate sandstones frequently bring silica, which they deposit in the pores between the sand grains. After a period there may result a solid quartz rock, or *quartzite*.

How can one tell quartzite from vein quartz?

Sometimes quartzite is pure white, and very difficult to distinguish from vein quartz, which has been deposited entirely from underground waters. A close scrutiny, especially with a magnifying glass, will often disclose the faint outlines of the close-packed rounded grains of the original sand. Even in thin sections under the microscope, vein quartz and quartzite are often similar, but examination generally shows the outlines of the sand grains in the quartzite, marked by a rim of clay or iron.

What is the nature and origin of shales?

Mud beds, when somewhat dried, become clay. On hardening, clay becomes shale, a rock distingushed by its softness, its fineness of texture, and its easy splitting into thin sheets along the bedding planes. Shales may be of any color, but are most frequently dark-colored, often black.

What is a slate?

When shale becomes still harder, it is called slate. The property possessed by slates of splitting into thin sheets, or *fissility*, is usually due to pressure exerted upon the rock subsequent to its deposition. Usually, also, the splitting does not follow the bedding planes, though sometimes it may.

How do limestones and marbles originate?

Limestone, dolomite and marble are intimately related. They begin as the accumulation of the shells of marine animals, often broken so as to form sand or mud; or, more rarely, they are chemically precipitated. These deposits harden into rocks. Limestones are of all degrees of compactness, from the slightly consolidated shell-mud to the dense semi-crystalline, generally dark blue, rock, which it is sometimes difficult to recognize as sedimentary. When limestones have been exposed to heat and pressure in the earth's crust, they become crystalline, and are then marbles. The fossils which are frequently found in limestones often become obliterated when the marble state is reached, but not always.

How does dolomite originate?

Lime-sands and limestones are generally carbonate of lime, with some impurities. Magnesia (magnesium oxide) has a great affinity for lime carbonate, and easily combines with it to form *dolomite*, a mineral containing 54.35 per cent calcium carbonate and 45.65 per cent magnesium carbonate. Magnesium salts are present in most waters,

especially in the ocean and in underground waters. Where sea-water becomes land-locked, and the magnesium and other salts concentrated, (as is the case in the Dead Sea and in Great Salt Lake, for example), the lime deposits which become precipitated are apt to be impregnated with magnesium and to change to dolomite. Limestone rocks that are permeated by underground magnesian waters may be similarly altered.

If a certain dolomite formation is everywhere of about the same composition, the alteration has probably been due to the first named cause; if the dolomite occurs chiefly along water-courses, such as fissures in limestones, and is of very irregular composition, the change has probably been due to the latter agency. Marbles are very frequently dolomitic or magnesian.

Example: In the lead and zinc mining region of southwestern Missouri, there are beds of magnesian limestone or dolomite of Silurian age. This limestone is magnesian wherever it outcrops and is evidently an original deposit. On the other hand, there are irregular deposits of dolomite immediately associated with the ore-bodies. This dolomite is generally contiguous to the limestone wall rocks, and appears to grade into them. Blocks of limestone are often found covered with a shell of such dolomite, evidently formed by the action of solutions containing magnesia upon the limestone.*

How can one tell limestone from dolomite?

It is next to impossible to distinguish dolomite from limestone by the appearance. In certain regions the

* Arthur Winslow, Missouri Geological Survey, Vol. VII, p. 448.

dolomite will have a different appearance from the limestone, being finer or coarser, or of a different color; but the test will not hold good for another district. The best way is to test with very dilute hydrochloric acid. A drop of this on limestone causes a lively effervescence, while dolomite is slightly or not at all attacked. This does not apply to strong acid. A thin section of dolomite under the microscope is like one of limestone, but may often be distinguished by the tendency of dolomite to be in small grains with perfect rhomboidal outlines, while calcite (lime carbonate) is more frequently a mass of interlocking irregular grains.

THE DISTINCTION BETWEEN BEDDING, CLEAVAGE, SCHISTOSITY, AND GNEISSIC STRUCTURE.

What are cleavage-planes?

When any rock, but particularly a shale, is exposed to pressure by the movements of the earth's crust, it is apt to break easily into sheets along certain planes determined by the direction of the applied forces. These planes are called *cleavage planes.* They may lie at any angle to the bedding planes, or may even coincide; they may be straight while the bedding planes are folded; in short, the two sets of parting planes have no relation to one another.

How can one distinguish between cleavage and stratification?

To be sure of stratification, one must look for layers differing in texture or mineral composition. In the case of conglomerates the pebbles typical y have their

longest diameter parallel to the stratification, for they have come to rest upon their flat sides, and not on end; in fossiliferous rocks the fossil shells have their long axis parallel to the stratification, for the same reason.* In short, any evidence of the original position of the sediments must be looked for. A rock may not split at all along its true bedding planes, while it may separate perfectly along cleavage planes which run across the stratification; but the cleavage must not for that reason be mistaken for bedding.

What are schists and gneisses?

Schists and gneisses have been mentioned in Chapter I as frequently the result of the metamorphism of sedimentary rocks.

A schist is a highly metamorphosed slate, which has become thoroughly crystalline, the minerals having a parallel arrangement. The individual crystals are generally relatively small. Further crystallization may produce larger crystals, and a less perfect parallel arrangement, when a gneiss results. Gneiss, as commonly understood, is composed of the same minerals as granite (feldspar, quartz, mica, hornblende, etc.) and differs from it by reason of the more or less marked arrangement of its minerals in bands. With variations in the mineral composition syenite gneiss, diorite gneiss, etc., are distinguished,

* An exception to this test of stratification planes is where rocks have been *stretched* by movements of the crust. In that case it sometimes happens that pebbles, and even fossils, are pulled out of shape, and so their long axes cease to have any relation to the original stratification.

possessing a mineral composition similar to that of the igneous rock from which they have been named.

How do we know that schists and gneisses may be formed from sedimentary rocks?

Not infrequently in schists, less often in gneisses, we may find evidence of sedimentary origin, in the shape of stratification, of pebbles, and (rarely) of obscure fossils. In other places no such evidence can be seen, and we cannot determine the origin of the rock, (except perhaps, by microscopic study), for schists and gneisses may also be formed from igneous rocks.

What is schistosity and gneissic structure?

Both schists and gneisses have strong banding, resembling stratification, but having no necessary connection with it. In schists, where the crystals are well arranged in parallel position, the rock splits very easily in the same direction, especially in mica-schist, where mica is an abundant mineral. This property is called *schistosity*. In gneisses, where the parallelism is not so strong, resulting only in a more or less marked banding, the banding is called *gneissic structure*.

What are the different kinds of schists and gneisses?

According to the minerals which they contain, schists and gneisses are given different names. With schists this name is usually taken from the predominant mineral. Thus, mica-schists are the commonest; and we have also garnet-schists, hornblende-schists, etc.

DIFFERENT GEOLOGIC PERIODS DURING WHICH SEDIMENTARY ROCKS HAVE FORMED.

How long is it that sedimentary rocks have been forming?

Studies of geologists have proved that the stratified rocks differ in point of age—that they have been continuously deposited during millions of years. At many places the sedimentary beds are several miles in actual thickness, and one can imagine what time must elapse to allow so much sediment to accumulate.

What proves the fact of these great periods of time?

The best proof lies in the fossils which the sedimentary rocks contain. By study of these remains or impressions of animals and plants a good idea of the history of the world has been obtained, and of the manner in which life changed, in the course of periods compared with which the historic period of man on earth is but as a day to a century.

How did life begin and develop on earth?

We do not well understand the beginning of life, for in the oldest rocks the traces of life are almost always destroyed by metamorphism. But when we first find a good record, there were already mollusks, crustaceans and worms; afterward fishes came in, and then reptiles; still later mammals, and finally the highest type of mammals—man. In the plant world there was a like gradual development and change.

How did the different geologic periods come to be so defined and named?

The science of geology is new. Within the last hundred years, geologists have studied, in different parts of the world, the fossils of certain groups of stratified rocks, and have applied names to the time periods covered by the fossils they have there found. These names frequently come from the name of the country where the rocks were first studied—as Jurassic, from the Jura mountains (part of the Alps); Cambrian, from Cambria (Wales); etc. Afterward, in other parts of the world, rocks containing similar fossils were also called Jurassic or Cambrian. Other terms came from some real or supposed peculiarity of the rocks of that period—thus, Carboniferous (meaning coal-bearing). At first all coal was supposed to occur in the rocks of this age; and conversely, all rocks of this age were expected to contain coal. More recently both propositions have been completely disproved, but the name remains. Other names are left to us from earlier and cruder attempts at age classification. Thus Tertiary and Quaternary remain from a division of rocks into primary, secondary, tertiary and quaternary. The first two of these terms have been dropped, the last two retained.

Does the classification of geologic time by periods represent a natural system?

The classification is more or less arbitrary and might be just as accurate if it were made up quite differently from what it is. Between one period and another we must not

imagine that there were sharp divisions. Life and the deposition of sediments often passed smoothly and uninterruptedly from one period into another. However, the classification is of accepted usage and enables general understanding.

What are the names of the geologic periods of time?

Following are the chief divisions, beginning with the oldest:

Archæan		No fossils. No known life.
Paleozoic	Cambrian	Each marked by characteristic fossils.
	Silurian	
	Devonian	
	Carboniferous	
Mesozoic	Triassic	
	Jurassic	
	Cretaceous	
Cenozoic	Tertiary	
	Quaternary	

What are the characteristics of rocks of the Archæan period?

The Archæan rocks contain no fossils and show no signs of life. Although it is probable that life existed at that period or during a portion of it, the traces have been obliterated. The Archæan rocks are usually metamorphic. They may be gneisses and schists, or massive crystalline rocks, like granites They occupy large areas of the earth's surface.

What are the characteristics of rocks of the Cambrian period?

The Cambrian rocks contain trilobites,[1] (often large), certain generally very small brachiopods, worm-tracks, some remains of fossil sponges, crinoids, etc.; also traces of seaweeds.

What are the characteristics of rocks of the Silurian period?

The Silurian rocks contain impressions of sea-weeds; some terrestrial plants, among them some members of the Lepidodendron[2] family, having much the habit of the spruce or pine tribe; trilobites[3] and many other crustaceans;[4] worms; very many graptolites[5] (feather-like animals); many mollusks,[6] especially brachiopods[7] and cephalopods;[8] also many lamellibranchs,[9] corals and crinoids.[10] The earliest fishes also occur, some of them of the shark tribe.

What are the characteristics of rocks of the Devonian period?

The Devonian rocks contain sea-weeds, lycopods[11] (ground pines) and ferns, equisetæ[12] or horse-tails, and conifers.[13] The animal life was varied. There were many sponges and corals, crinoids, brachiopods, and other kinds of mollusks, and a few trilobites. Fish are frequently found, belonging to the shark and other tribes. The Devonian has been called the Age of Fishes.

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[1] For the explanation of this and following terms, see pp. 44-51. [2] See p. 51. [3] See p. 47. [4] See p. 47. [5] See p. 45. [6] See p. 45. [7] See p. 47. [8] See p. 46. [9] See p. 46. [10] See p. 45. [11] See p. 51. [12] See p. 51. [13] See p. 50.

What are the characteristics of rocks of the Carboniferous period?

The Carboniferous was marked by an abundance of vegetation, whose remains or imprints we often find as coal or as fossils in the rocks. There were lepidodendron and sigillaria,[1] and various ferns, conifers and calamites,[2] (a genus of horse-tails). As to the animal life, there was a great abundance of crinoids or sea-lilies; also numerous brachiopods, cephalopods,[3] etc. Besides fishes, remains of amphibians[4] occur, some snake-like, some lizard-like, some frog-like. On the land were insects, (cockroaches, etc.) spiders and centipedes, and true reptiles—snakes, saurians,[5] and turtles.

What are the characteristics of rocks of Mesozoic age?

The Triassic, the Jurassic and the Cretaceous periods together constitute the Mesozoic age, called the Age of Reptiles. In this age came the first mammals, the first of the common or osseous[6] fishes, the first palms and angiosperms.[7]

What are the characteristics of rocks of the Triassic period?

The Triassic had neither the sigillarids nor the lepidodendrids of the Carboniferous era; but many cycads,[8] besides ferns, horse-tails, and conifers. As to animals, some brachiopods and lamellibranchs were abundant; also ammonites.[9] Fishes and reptiles, the latter including the gigantic dinosaur,[10] were also plentiful.

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[1] See p. 51. [2] See p. 51 [3] See p. 46. [4] See p. 48. [5] See p. 49. [6] See p. 49. [7] See p. 50. [8] See p. 50. [9] See p. 47. [10] See p. 49.

What are the characteristics of rock. of the Jurassic period?

The Jurassic contains, besides many characteristic radiates,[1] sponges and mollusks, (brachiopods, lamellibranchs, cephalopods, etc.) remains of gigantic reptiles, including the flying-reptiles or pterodactyls,[2] the ichthyosaurus,[3] tortoises, etc.; also some mammals. Fishes flourished.

What are the characteristics of rocks of the Cretaceous period?

The Cretaceous plants were marked by the first great development of the angiosperms (including all plants with a bark, except the conifers and cycads). This class embraces the oak, willow, maple, etc. The smaller marine animals have contributed shells in great variety and profusion to the Cretaceous sediments. Rhizopods with tiny shells (foraminifers[4]), were abundant, and constitute most of the chalk beds. Sponges and corals were of great importance. The oyster family flourished, and many others. Sharks and other fishes were common; reptiles were numerous, among them true sea-serpents, as much as seventy-five feet long. Turtles lived, and also birds, some of which possessed pointed teeth.

What are the characteristics of rocks of the Tertiary period?

The Tertiary is called the Age of Mammals, for during this period mammals flourished. Yet most of the Tertiary mammal species are now extinct.

The Tertiary beds often contain plant remains, belonging

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[1] See p. 45. [2] See p. 49. [3] See p. 49. [4] See p. 44.

to species of oak, maple, dog-wood, magnolia, fig, palm, etc. The mollusks comprise many species of oyster, clam, and other lamellibranchs, but few brachiopods. Crabs, insects, fishes, etc. were plentiful. Crocodiles, snakes, and turtles abounded. There were many large mammals, including now extinct species of elephant, tapir, rhinoceros, horse, tiger, lion, wolf, peccary, etc. The remains of all of these are found in the western United States. In the sea there were whales, dolphins, seals and walruses.

Example: A quarry near Carson, Nevada, now used as a State prison yard, is cut in grayish sandstones, whose bedding is such as to indicate that they were deposited at the mouth of an ancient stream. When the sandstone was removed down to two shale layers, these were found literally covered with the tracks of many species of birds and mammals, including the mammoth, the deer, the wolf, many birds, a horse, and tracks resembling those of a man, but which may have been made by some animal. The footprints and some associated bones indicate a probable very late Tertiary age. These remarkable tracks were exposed and trampled over by horses and men for eight or ten years, without attracting any especial attention.*

What are the characteristics of rocks of the Quaternary period?

The Quaternary in called the Age of Man, for in this period the human race began to flourish. During this age came the Glacial Period or Ice Age, when a vast glacier or glaciers covered the northern part of North America, with their southern margin running irregularly across the northern and central part of the present United States. These

* J. Le Conte, *Proceedings* California Academy of Science, Aug. 27, 1882.

glaciers spared most of Alaska and some other areas, but everywhere else ground off the cliffs and hills, and left, on melting, vast deposits of boulders and gravels. Thus in the eastern United States the southern and central portions, which are unglaciated, are strikingly different from the rocky, bouldery, often barren glaciated areas of the north. In the Western States the glacier did not extend far south of the present Canadian boundary.

In the early part of the Quaternary flourished many great mammals, of species now generally extinct. These comprised gigantic mastodons, elephants (mammoths), lions, hyenas, bears, wolves, beavers, etc. Man probably lived in the later Tertiary period, but evidence of his existence is first complete in the Quaternary. He was contemporary with the hairy mammoth and other extinct species, which he has survived.

How can one tell to what period a given rock belongs?

The only reliable way to identify a stratified rock, as belonging to one of these periods, is by study of the fossil remains which it contains. These will tell in what stage or the world's history the sediment was laid down. To the paleontologist, who has made a careful study of extinct animal forms, it is generally possible, on seeing a group of fossils, to refer them to one of the great periods given. But to the casual observer, the differences are not so striking as to be retained without study and careful comparison. There are, to be sure, certain broad signs, which he may use as guides, to a limited extent. Rocks containing large numbers of trilobites, with few other fossils,

are probably Cambrian, or Silurian, most probably the former. Rocks with graptolites are probably Silurian. Rocks containing plant remains, if these are largely reed-like and otherwise unlike any of our common trees, are probably Carboniferous, perhaps Devonian. If the plant remains consist of leaves resembling those of our modern trees, the rocks are probably Cretaceous or Tertiary. In the same way, rocks containing fossil shells almost exactly like those which are now occupied by living animals on the sea-shore, are probably Tertiary, and in proportion as the unlikeness increases, we can suspect an older age. A great abundance of crinoids suggests the Carboniferous. Abundance of sponges, corals and large brachiopods, with fewer lamellibranchs, suggest the Carboniferous or Devonian. Predominance of lamellibranchs indicates a probable age not older than Triassic, etc.

With a little practice in observing rocks of known age, one can tell ordinarily, although by no means always, a Paleozic rock, a Mesozoic rock, or a Tertiary rock, from the general look of the fossils, even if one cannot determine a single species. Where a certain series of strata has been determined by paleontologists, one can attentively examine the fossils contained, and can then very likely recognize beds of the same age in another part of the same district or even in another district.

CHARACTERISTICS OF THE DIFFERENT FOSSILS.*

The fossils which have been referred to belong mostly to

* The descriptions and definitions under this head are adopted directly from Dana's 'Manual of Geology.'

the animal kingdom; some of them to the vegetable kingdom.

How is the animal kingdom divided?

The animal kingdom is divided into five sub-kingdoms. Beginning with the lowest they are:

1. Protozoans.
2. Radiates.
3. Mollusks.
4. Articulates.
5. Vertebrates.

What are protozoans?

Protozoans are minute animals, (usually from a 100th to a 10,000th of an inch in length.)

They have no external organs save a mouth and minute thread-like organs, and no digestive apparatus beyond a stomach. The stomach and the mouth are sometimes wanting. There is no heart or circulating system beyond a palpitating vesicle.

What are rhizopods and foraminifers?

Among protozoans, the rhizopods are of especial interest. The shells are usually much smaller than the head of a pin. The most common kinds have calcareous shells called foraminifers, and these have contributed largely to the formation of the limestone strata. They consist of one or more shells, and the compound kinds present various shapes.

What are radiates?

Radiates have a radiate structure, like a flower—that is, they have similar parts or organs repeated around a vertical axis. These animals have a mouth and stomach for eating and digestion, and are widely diverse from plants, although resembling them in their radiate arrangement of parts.

What are crinoids?

Among the radiates, crinoids are animals like an inverted star-fish or sea-urchin, standing on a stem like a flower.

What are graptolites?

The graptolites were ancient, delicate plume-like animals which belonged in the sub-kingdom of radiates.

What are mollusks?

Mollusks possess a soft fleshy bag, containing the stomach and viscera. They do not possess a radiate structure nor jointed appendages. Similar parts are repeated on right and left sides of a median plane, and not around a vertical axis, as in radiates.

How are mollusks subdivided?

Mollusks are divided into:

1. Ordinary mollusks.
2. Ascidian mollusks.
3. Brachiate mollusks.

The ordinary mollusks are divided into:

1. The acephals, or headless mollusks, the head not

being distinctly defined in outline; as the oyster and clam.

2. The cephalates, having a defined head; as the snail.
3. The cephalopods, having the head furnished with long arms (or feet); as the cuttle-fish.

What are lamellibranchs?

The acephals, or headless mollusks, are illustrated in the group of lamellibranchs. These common species are well known as bivalves. One valve is on the right, and the other on the left, of the animal. The clam and the oyster are familiar examples.

What are gasteropods?

In the cephalates, one of the two groups are the gasteropods. These are contained in univalve shells (shells all in one piece). The animal crawls on a flat spreading fleshy organ called the foot. The snail is a familiar example.

What are cephalopods?

Cephalopods, or cuttle-fishes, are of two kinds, one having external shells and four gills; and another having sometimes internal shells, but not external, and having but two gills. The external shells are distinguished from those of the gasteropods or ordinary univalves by nearly always having transverse partitions—whence they are called chambered shells. They may be straight or coiled, but when coiled are usually coiled in a plane, and not a spiral. The animal occupies the outer chamber of the shell. The nautilus is an example.

Modern cephalopods are almost exclusively naked species, such as the cuttle-fish and squid.

What are ammonites?

The ammonites are a genus of cephalopods, and have very beautiful and often large coiled and fluted shells.

What are brachiopods?

Among brachiate mollusks, brachiopods have a bivalve shell, and in this respect are like ordinary bivalves. But the shell, instead of covering the right and left sides, covers the dorsal and ventral sides, or its plane is at right angles to that of a clam. Moreover, it is symmetrical in form, and equal on either side of a vertical line. The valves are almost always unequal; the larger is the ventral, and the smaller the dorsal.

What are articulates?

Articulates consist of a series of joints or segments. The legs, where any exist, are jointed, and there is no internal skeleton. The articulates include worms, crustaceans, and insects.

What are crustaceans?

The crustaceans have the body in two parts—the front consisting of a head and thorax, the hinder part of the abdomen. Crabs, lobsters, and shrimps are examples.

What are trilobites?

Among crustaceans, the trilobites existed only in Paleozoic time. They had jointed bodies with a crust-like

exterior. They are more like the horse-shoe crab of the Atlantic coast than any other living species.

What are vertebrates?

The fifth animal sub-kingdom comprises the vertebrates. These have a jointed internal skeleton, and a bone-sheathed cavity along the back for the great nervous cord, distinct from the cavity of the viscera.

How are vertebrates divided?

The classes of vertebrates are:

1. Mammals, which are the highest branch of the animal kingdom. They suckle their young and breathe with lungs. Ordinary quadrupeds (four-footed animals) are all mammals.

2. Birds produce their young in the egg form. They have a heart of four cavities; they breathe by lungs, are covered with feathers, and are adapted for flying.

3. Reptiles produce their young in the egg form. They breath by lungs, have a heart of three or four cavities; and are naked or covered with scales. Examples are crocodiles, lizards, turtles, and snakes.

4. Amphibians produce their young in the egg form. When young they breath by gills, and afterward by lungs alone. They possess a heart with three cavities, and are naked or covered with scales. Examples are frogs and salamanders.

5. Fishes usually produce their young in the egg form. They possess a heart, usually of two cavities. They breathe by gills, and are naked, or covered by scales.

What are osseous fishes?

The osseous fishes or teliosts include nearly all modern kinds, except the sharks and rays. They usually have membranous scales. They are not known among fossils before the Middle Mesozoic.

How are reptiles classified?

Reptiles are divided into snakes, saurians, and turtles. The saurians vary in length from a few inches to fifty feet.

What were dinosaurs and pterosaurs?

Among the saurians the tribe of dinosaurs, reptiles of great size, now extinct, possessed some mammalian and many bird-like characteristics.

Another group were the pterosaurs or the flying saurians. The pterodactyls were the most common genus. The little finger of the forefoot was excessively prolonged, and from this a membrane extended to the tail and made a wing for flying. The remaining fingers were short, and furnished with claws. They had the habits of bats, and wings of a similar character.

What were ichthyosaurs?

The ichthyosaurs were a genus of the group of enaliosaurs, or swimming saurians. They were gigantic animals, 10 to 40 feet long, having paddles somewhat like the whale, long head and jaws, and an eye of enormous dimensions.

How is the vegetable kingdom divided?

The vegetable kingdom is primarily divided into cryptogams, which have no distinct flowers or proper fruit, (such as ferns and sea-weed), and phenogams, having distinct flowers and seed, (such as our ordinary trees and plants).

How are the phenogams subdivided?

The phenogams are divided into:

1. Gymnosperms. The plant has a bark, and grows by an annual addition to the exterior of the wood, thus forming rings of growth. The flowers are very simple, and the seed naked. Examples are the pine, spruce, hemlock, etc. Gymnosperms include: (1) Conifers. (2) Cycads. The conifers include most of the common evergreen trees. Their wood is simply woody fibre, without ducts. The cycads had the habit of palms, while related to the pine tribe.

2. Angiosperms. Growing by external annual rings, like the gymnosperms; having regular flowers and covered seeds. Examples are the maple, elm, rose, etc.

3. Endogens, having regular flowers and seed, but with no bark and no rings of growth. In a transverse section of a trunk or stem, the ends of fibres are shown. Examples are the palm, Indian corn, lily, etc.

How are the cryptogams subdivided?

The cryptogams are subdivided into:

1. Thallogens. Consisting wholly of cellular tissue;

growing mostly in fronds without stems, and in other spreading forms; as, (1) Algæ, or sea-weeds. (2) Lichens. (3) Fungi, or mushrooms.

2. Anogens. Consisting wholly of cellular tissue; growing up in short, leafy stems; as, (1) Mosses. (2) Liverworts.

3. Acrogens. Consisting of vascular tissue in part, and growing upward; as, (1) Ferns. (2) Lycopods (ground pine). (3) Equiseta, or horse-tail; and including many trees of the coal period.

What were lepidodendrids?

Among the fossil lycopods, the lepidodendrids (tall trees, with the exterior embossed with scars in alternate order,) were of many kinds. In foliage, they resembled the pines and spruces of the present day.

What were sigillarids?

The sigillarids differed from the lepidodendrids in having the scars in vertical order. The trunk was woody, but not firm within; and it had a large pith.

What were calamites?

In the Paleozoic, the equisetæ, or horse-tails, were represented by plants called calamites. They had a reed-like appearance, with jointed stem, and finely furrowed surface.

The Order of Succession as Found in Actual Practice.

Is the succession of geologic periods, as previously stated, always shown in the sedimentary rocks of a given district?

Not always; indeed, not usually. Any one of the geologic ages may not be represented at all, may be represented by very thin beds, or by strata thousands of feet thick. Often rocks of only a few of the geologic ages are present. Tertiary beds may rest directly upon those of the Cambrian age; or the Quaternary may rest upon the Archæan. In fact, there is every possible combination.

What is the reason for this lack of uniformity?

In a certain part of the earth's surface there may have been no sediments during a certain age or ages. If the region was a land area during any period this would be the case, for stratified rocks are laid down in water. Again, after the sediments were formed, during a certain period, they may have changed into land, and have been stripped off and carried away by the erosion of the rivers. Then, when the land became again submerged and new strata were deposited in their place, the new beds may have come to rest on those of an age much greater than the series usually found next underneath them.

What is an erosion gap and an unconformity?

In the case just mentioned, the line of contact between the two series of strata will be irregular, for the newer beds will have been deposited over the hills and hollows of the older topography, although the stratification in both

series may be parallel. This is called an *erosion gap;* sometimes an *unconformity by erosion.*

Frequently, in the interval between the deposition of the earlier series and that of the later one, there occur movements in the earth's crust, so that the beds of the older series are bent or folded; then the new series does not have its stratification parallel, but rests discordantly on the bent and worn edges of the old strata. This is a true *unconformity* (Fig. 2).

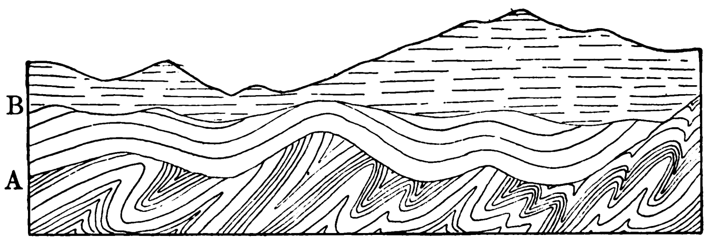

Fig. 2. Ideal sketch to illustrate unconformities. a. Earlier line of unconformity; b. Later line.

Relation of Physical Characters to Geologic Age.

Can one tell from the kind of rock what age it belongs to?

In general, the nature of the strata, whether limestone, quartzite, etc., is of little value in determining to which of the geological periods it belongs. A certain stage of the Carboniferous, for example, may be represented by a sandstone in one district, a limestone in another.

Is a given bed necessarily of one kind of rock throughout?

A bed may pass laterally from one kind of rock into another (as from a sandstone into a limestone), within a space of a few miles or even much less.

Example: On the Kuskokwim river, Alaska, the writer* observed a series of interbedded sandstones and shales, where the sandstone passes laterally into shale in a remarkable way. A thick bed of sandstone splits into separated beds which become alternate with beds of shale, and these rapidly grow thinner as the shale beds increase in thickness until the shale forms nearly the entire rock (Fig. 3).

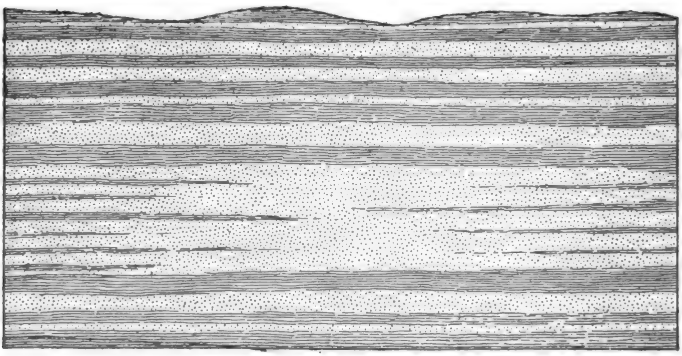

Fig. 3. Sketch of cliff on Kuskokwim river, Alaska, showing sandstones and shales passing laterally into one another.

What is the explanation for this transition?

If one considers sediments now being formed, one will find such transitions common along the sea-shore. For example, there is found at one point mud, at another sand, at another gravel or cobbles, all being deposited at the same time. When such a deposit is hardened and becomes stone, it will show within a single bed the change from a shale to a sandstone, and from a sandstone into a conglomerate.

* 20th Annual Report United States Geological Survey, Part VII, p. 125.

Can strata be identified by their physical characters?

If only the foregoing exception is remembered as a guard against over-confidence, it is possible to trace certain strata a long distance by their physical characters, which they may retain for hundreds of miles. Sometimes the peculiarities of certain strata are so marked that, when one finds in adjacent districts rocks possessing these peculiarities, there is a strong suggestion of identity of age.

Example: The lithological identity of the peculiar parti-colored, thin-bedded shales, lithographic limestones and quartzite of the Parting Quartzite series in Aspen, Colorado, with Devonian strata described by Mr. C. D. Walcott from Kanab creek, Utah, so impressed the writer, that other conditions being favorable, he provisionally classified the Aspen beds as Devonian, although the localities are hundreds of miles apart. This correlation was afterward borne out by the discovery of Devonian fossils in the Aspen beds.

Yet correlation from physical characters alone, without sufficient guardedness and auxiliary evidence, has frequently led into the most awkward errors.

Does a certain kind of rock ever constitute beds of the same age over large areas?

A certain character of strata may persist in some instances over a wide region—even over large portions of continents. Some physical features of strata of a certain period seem to be of almost world-wide occurrence. In rocks belonging to the Triassic, all over the world, there is

an astonishing quantity of massive red sandstone; yet all massive red standstones are by no means Triassic, and conversely, all Triassic rocks are not red sandstone.

Comparison and Correlation.

Mode of Determining the Relative Age of Different Strata.

How can one determine the relative age of different series of strata in contact with one another?

The relative age of a series of strata may often be determined by making reference to other strata, the age of which is definitely known. The first rule to be observed, is the simple *rule of superposition*, by which the upper of two series of strata, or of two beds, is usually the younger. This is to be applied not only where the beds are horizontal but where they are folded; it is easy to do this, except in the rare case where the folding has been so great that some beds have been overturned, and the normally lower ones come on top. In this case the study of the folding, the fossils present in the rock, etc., will afford the data requisite for solving the problem.

This rule does not necessarily apply where a fault separates the two beds in question.

How may the relative age of different series of strata, not in contact with one another, be judged?

Where two rocks are not found in actual contact, there are other tests of their relative age. Of two rocks close together, the more metamorphosed or hardened one is probably the older; likewise, that one which shows most

folding and faulting, and other evidence of disturbance, is probably the older. One rock, such as conglomerate, may contain pebbles which have been derived from the other: in this case the conglomerate is clearly the younger. Many such tests will present themselves to the careful investigator.

Mode of Correlating Similar Strata in Adjacent or Separated Regions.

How are similar strata in different localities identified as such?

This point has already been dwelt upon, but may be briefly summarized.

The correlation or matching of similar strata in adjacent or separated regions is usually done by means of the fossils which they contain. If these fossils are nearly the same in two different localities, the beds may be correlated; or, if, although not belonging to the same species, they are known to represent a similar stage in the development of life.

When fossils are lacking, the physical characteristics may serve as a basis for correlation. The bed in question may be traced wholly or partly from one district to another; or, if its peculiarities are very striking, a correlation between separated districts may often be made without tracing out the intervening portions. Thin beds are usually traced out and correlated by their physical characteristics, which are apt to be more definitive in this case than fossils.

THE ASSOCIATION OF VALUABLE MINERALS WITH CERTAIN STRATA.

What is the commercial application of the knowledge of the principles concerning strata?

Whenever valuable minerals are confined wholly or partly to a certain bed or beds, the ability to recognize and trace that bed in different localities often leads to the discovery of new mineral districts and of new mines.

General Relations of Stratified Ores.

How is it that minerals are sometimes preferentially associated with a certain sedimentary bed or beds?

The association of a valuable mineral with certain sedimentary beds may be either primary or subsequent. That is, the mineral may have originally been precipitated in bed form, along with the other strata, or it may have been introduced into the beds long after their deposition.

Among valuable minerals known to be deposited originally in bed form, we may cite, besides coal, some gypsum deposits, salt beds and many other non-metallic minerals. In this way metallic minerals are also deposited in a greater or less state of concentration. Iron and manganese are deposited both in bogs and in the ocean depths; and in some rich muds copper in slight amounts and, to a certain extent, even silver and gold are precipitated. Many of these first named deposits afford workable minerals just as they are deposited; others, especially those of the less common metals, require further

concentration by percolating waters, but in the end the ore will still be confined to the parent bed or its neighborhood.

Ores introduced by circulating waters into strata, subsequent to their formation, often choose one bed in preference to another in consequence of some chemical or physical peculiarity favorable to deposition: and thus the resultant ore-body takes on a bedded form.

Example: In Piemonte, near Brosso, Italy, are beds of specular iron (hematite) and pyrite regularly interstratified with beds of limestone and mica-schist. Nearby, at Traversella, are deposits of pyrite, magnetite and copper pyrite in dolomite. At both these places the deposits are confined to the flanks of an intrusive quartz-bearing diorite, and the chief ore-deposits are accompanied by garnet or hornstone (altered and hardened limestone), together with other metamorphic rocks. The conclusion has hence been reached, that the ores are due to the influence of the intrusive rock; that first gases, and later hot springs, both emanating from the diorite, attacked and mineralized the intruded strata. The limestone strata were more strongly affected than the mica-schists and were replaced by ores, so that they now are represented by ore-beds intercalated in the schists. Strong fractures permitted the gases and water to penetrate far from the diorite, so that the mineralization was extensive.*

Is it important to tell whether a bed of ore is primary or secondary?

Such a distinction is important, for the reason that in the first case the ore will invariably follow its regular bed,

* V. Novarese, Bull. Com. Geol. Ital. Vol. XXXII, pp. 75–93, 1901.

while in the second we must be always expecting it to deviate from it or to occur in other forms. This latter caution must also be maintained in regard to those primary bedded deposits which have undergone secondary concentration by circulating waters. These waters, besides concentrating the ore within the parent bed, are likely to carry it out and to form ore-deposits at a distance from it.

What chief points must one keep in mind in following an ore-bearing stratum?

In any case one of the chief things is to be able to trace and recognize the same bed in different places. Whether the occurrence of ore in bedded form is primary or secondary, it must be associated with a fairly constant character of the rock. If the deposit is original, the conditions which brought about the deposition of the same valuable mineral in various places must have given rise to other uniform physical characters. If it is secondary, the physical or chemical character, which determined the precipitation of ore along a certain bed, must be present wherever we can reasonably look for a continuance of that ore If a limestone bed containing replacement deposits passes laterally into a sandstone, the ore may be poor or wanting in the sandstone. If a shale bed, which by its impermeability or its organic matter has determined the deposition of ores in or near it, passes into a sandstone or limestone, again we must look for a change, and, very likely, the disappearance of this ore-horizon. For this reason, in tracing an ore-horizon, physical and chemical points are among the most valuable means of identification,

and where such points fail the chances are that the ore-horizon fails too.

Do ore-bearing strata ever extend as such for long distances?

Often a certain bed may be traced by its physical characters hundreds of miles, and is everywhere a valuable indication of contained ore.

Example: In the Lake Superior district, the ore-deposits are confined to a certain set of beds, easily recognizable by their peculiar physical characters. These beds make up the iron-bearing formation—they are sometimes slaty, sometimes massive, generally dark-colored rock—and by tracing them vast ore-deposits are continually found. This point is brought out in the following quotation from Mr. Oscar Rohn.*

"It may be well to recall that the iron ore-deposits of the Lake Superior district always occur in certain characteristic formations, called iron-bearing formations, which are associated with a series of conglomerates, quartzites, slates, and vein stones. . . . . So well understood and so generally recognized is the association of ore-deposits with a characteristic rock formation that in all well-directed prospecting the limits of the formation are sought, and underground work confined to the area within these limits."

How may the presence of a known ore-bearing stratum be recognized in a place where it does not outcrop?

The relation of an ore-bearing bed to other beds lying

* *Engineering and Mining Journal*, Vol. LXXVI, p. 616.

above and below should be studied and borne in mind. Often where the ore-bearing bed is not exposed at the surface, or is covered with surface débris, the recognition of a bed having a known relation to the ore-bed leads to the discovery of the latter and its contained ore-deposits.

Preferential Association with Certain Geologic Periods.

Are certain minerals preferentially associated with certain geologic periods?

To a limited and unreliable extent, even in the most favorable cases: generally not at all. Formerly this association was thought to be very important, however.

A famous and able geologist, Sir Roderick Murchison, as late as 1851 and 1859, made the statement that the chief sources of gold were in Paleozoic rocks, particularly in the Lower Silurian,—an opinion largely based on a fragmentary knowledge of Australian geology. Since then, in Australia, gold has been worked in Carboniferous, Devonian and Silurian rocks, and even in the Triassic and Jurassic; in South Africa the gold is largely in Devonian strata.

However, when we come to consider the world's great mining regions, we observe that it is indeed the older strata which in many cases carry the ores. The older rocks have had more time than the younger ones and more opportunity to become the seat of ore-deposition; they have also been, in most cases, deeply buried by the younger strata and so brought under such physical conditions of heat and pressure as are conducive to ore-con-

centration; under these conditions they have been pierced by intrusive rocks and subjected to all the accompanying processes of alteration and concentration.

To what geologic period do metalliferous veins generally belong?

Metalliferous veins seemed to have formed at every period of the world's history. As shown in the first chapter, they are the result of concentrating by agencies which have been active since the earliest age down to the present day. The age of veins, as actually proven, is extremely various, ranging from the Archæan through the Paleozoic, Mesozoic and Tertiary. Passing over the cases of veins and other ore-bodies belonging to older periods, we may mention that, in America, the rich silver districts of Leadville and Aspen, Colorado, and Eureka, Nevada, are of Tertiary age. Moreover, in the Monte Cristo district, Washington, the present writer has reached the conclusion that the veins are chiefly Quaternary (Pleistocene). At Steamboat Springs, in Nevada, the actually escaping waters have deposited silica along the fissures which they traverse. This silica often contains sulphide of mercury, in some quantity, and traces of gold. Similar phenomena have been noted in other places.

Example: Workable deposits of cinnabar and stibnite (sulphides of mercury and antimony) at Monte Amianta and other places in Tuscany, Italy, have formed subsequent to early Pleistocene volcanic eruptions (andesite and trachyte). The cinnabar is found in the volcanic rock as well as the associated sediments, and has formed by

preference in limestone beds. The stibnite is closely connected with the cinnabar, and is associated with arsenic sulphide (realgar), pyrite and limonite, and sulphur. Most of the ore-deposits are intimately connected with sulphur springs or emanations of sulphuretted hydrogen, which are accompanied by incrustations of sulphur, and silicious sinter which sometimes contains cinnabar.*

In opened mines and in placers it has been found that surface waters still precipitate all sorts of metals, even gold, from solution.

Example: The formation of lead and zinc sulphides is now taking place in the Missouri mines. An instance may be cited where an old tunnel near Joplin, driven through shales, became filled with water and was left so for ten or twelve years. In 1898, when it was re-opened, the surface of the shales, on the roof and sides of the tunnels, was found to be thickly encrusted with minute crystals of blende. In places, the blende was deposited on the pick-marks made when the tunnel was run.†

Can any statement be made concerning the most favorable geological age for ore-deposition?

The ore-deposits of earlier ages have been exposed, along with the containing rocks, to destruction by erosion; and, even where the containing rocks have not been removed, circulating waters have very often attacked the ores and transformed them wholly or partly into secondary or subsequent deposits. On the other hand, ores of compara-

* B. Lotti, *Zeitschrift für praktische Geologie*, 1901, pp. 41-46.

† W. P. Jenney, *Transactions* American Institute Mining Engineers, Oct., 1902, p. 26.

tively recent date, such as those of the Tertiary, will, in mountain regions, have undergone only the right degree of erosion for laying them open to the eye of man. So it is possible that the younger ore-deposits will be found to preponderate over the older ones, among the important districts actually exploited.

That is to say,—*other things being equal, important ore-deposits are rather more likely to occur in rocks belonging to the older geologic ages than in the younger ones; and their date of formation is more apt to belong to the younger geologic ages than to the older ones.*

What is in general the age of primary bedded deposits?

In river beds and on sea-beaches, gold-placers, tin-placers, etc., are today being formed, as they have been in past ages. Most of the world's productive placers are Quaternary, for these are easily found and have not been destroyed by erosion, as is the case with many of the older surface deposits. Yet in California, British Columbia, and Australia, Tertiary gravels, especially when protected by overflows of lava, have afforded immense wealth. Similar deposits exist in various older formations. Some authorities consider the Witwatersrand gold-bearing conglomerates, which occur amid a Devonian formation, as beach placers of that period; and placers of Cambrian and even pre-Cambrian age have been described.

At the present day, also, iron, manganese, gypsum, etc., are being chemically precipitated in bed form in the bottoms of lakes, seas and oceans; and this process is known to have been active during the past ages.

Is it true that different geologic ages have no special characteristics as regards mineral deposits?

It seems to be the case that in the different geologic ages the general conditions varied more or less uniformly; and in some of these ages the conditions for forming certain mineral deposits were better than in others.

Are coal and oil deposits confined to certain geologic periods?

At certain periods of the earth's history vegetation flourished very rankly and swamps were very abundant, enabling the preservation of accumulated layers of vegetable matter, which thus became a part of the strata of that period, and, by consolidation and metamorphism, have turned into lignite, soft or hard coal. The Carboniferous period was favorable to this process, and much coal was formed then. It was thought, indeed, at one time, that coal was formed only in this period, but since then it has been found in quantity in other formations. In Virginia, there is good coal in Triassic strata. In the Western United States, great quantities of coal are found in the Cretaceous, and on the Western coast, especially in Alaska, it is abundant in the Tertiary. In Alaska we can see at the present day the first process of coal formation in the great areas of swamp-peat, which is often many feet thick, and shows the closest resemblance in habit to the late Tertiary lignites of the same region. When these peat-swamps shall have been covered up by later strata, and consolidated and changed by pressure, they will become coal-beds.

Thus we see that we cannot confine the formation of coal-beds to any one geologic period. Yet we may still regard the Carboniferous rocks as especially likely to contain such deposits, while we should hardly expect to find good coal-seams in the Cambrian and Silurian.

These favorable conditions, during a certain period, were not world wide. At one place was marshy land, at another the ocean. In the Carboniferous, over eastern North America, there was much land, lagoons and flourishing vegetation; in the western United States there was generally deep sea. So in the eastern area we find coal plentifully in the Carboniferous, especially in certain beds, which can sometimes be traced for hundreds of miles; while in the western area the Carboniferous was not especially a coal-bearing period. Conversely, in the Rocky Mountain region the Cretaceous is the great coal-bearing horizon; but this is not the case in the eastern United States.

Oil is another mineral for which the conditions of formation have been more favorable in certain periods than in others. Abundance of organic life during these periods seems to have been the favoring circumstance, for the organic matter has by its decomposition formed the oil.

Are there minerals other than coal and oil which were deposited more abundantly in certain periods?

In some periods, more than in others, there appear to have been large areas of shallow evaporating seas, from which certain mineral substances were precipitated. Thus, both in the old world and in the new, Permian strata (the

youngest part of the Carboniferous age) contain, in many places, deposits of salt, gypsum, etc.

Is a knowledge of fossils of value in identifying the same ore-bearing stratum in different districts?

Besides the identification of an ore-bed by its physical characteristics, it is frequently possible to recognize it by means of its contained fossils. The fossils are the only safe evidence of identity in age, when the districts to be compared lie some distance apart. Beds having the same physical appearance may, and do, occur in many ages, while perhaps only in one did there exist the finer conditions which were favorable to the production of deposits of valuable minerals.

Example: Dr. Le Neve Foster relates that a French inspector of mines. M. Meugy, hearing of the discovery of phosphate of lime in a certain part of the Cretaceous in England, and knowing from fossil evidence that beds of the same age existed in France, concluded that the French beds might also contain phosphate deposits—a conclusion which was amply verified by prospecting.

Preferential Association with Certain Kinds of Sedimentary Rocks.

Are certain kinds of minerals preferentially associated with certain kinds of sedimentary rocks?

Certain kinds of rocks are sometimes preferred by certain minerals for deposition; but there is no regular rule. The association may be either primary or secondary.

Contemporaneous Deposition of Ores and Strata.

In what cases is such association primary?

In coarse sediments which are evidently shallow water or shore-formations, such as coarse impure sandstones, conglomerates and clays, mixed with vegetable material and plant remains, we may suspect coal or oil, or natural gas.

Example: The petroleum-bearing strata of all periods and of all parts of the world show, according to Dr. Rudolf Zuber,* a remarkable resemblance in their formation and composition. Everywhere they are bituminous clay-shales, and variegated, mostly bright-colored, clays, interstratified with sandstones and conglomerates. Limestones, which may also occur in such series, contain tarry materials, but rarely true petroleum.

There is a surprising resemblance between the red and green clays and shales of an American Paleozoic oil-bearing formation, with oil-bearing formations in the Jurassic of Germany, and in the Eocene of Galicia. The oil-bearing strata of the Upper Triassic in the western part of the Argentine Republic are like the middle Tertiary (Oligocene) oil-bearing rocks of the Carpathian Mountains; the green oil-bearing shales, lying between the Jurassic and the Cretaceous, in the northern part of the Argentine Republic, cannot be distinguished from the Galician Eocene strata. The oil-bearing strata at Baku in the Caucasus are identical in appearance with the Carpathian Oligocene shales and sandstones.

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* *Zeitschrift für praktische Geologie*, March, 1898, p. 85.

Deposits of salt, gypsum, etc., may be looked for especially in connection with red sandstones. This association has been explained by the fact that when sea-water evaporates, the first precipitate is oxide of iron (which gives the red color to the rocks); this is followed by gypsum and then by salt.

Can one admit such an association for metallic minerals?

It is as yet an open question as to whether copper may not also be admitted to the same association. In Germany the Mansfeld *Kupferschiefer* (copper-slate) is a thin bed of bituminous shale lying between two thick deposits of Permian sandstone. The ore contains, besides copper, silver, lead, zinc, antimony, mercury, nickel and cobalt. This *Kupferschiefer* outcrops over a large district and frequently there is copper either in it or in the other beds of the Permian. At St. Avold and Wallerfangen, (also in Germany), copper ores which occur in Triassic sandstone, have been supposed to be contemporaneous with the enclosing rock. In Utah, in the Silver Reef district, red and gray Triassic sandstones and shales contain bedded copper-silver deposits. In the Nacimiento mountains in New Mexico copper ores occur in Triassic sandstones, associated with plant remains. Similar deposits, although without the organic remains, have been described by Prof. W. P. Blake as occurring in Arizona. Prof. James F. Kemp gives many examples of copper ores in Triassic and Permian sandstones. "Copper ores," he says, "are very common throughout the estuary Triassic rocks of the

Atlantic coast."* In the Permian of northern central Texas there are three separate copper-bearing zones, forming three lines of outcrop that extend in a general northeasterly direction over a range of about three counties.

May not these bedded deposits of metallic minerals have been introduced into the beds subsequent to their deposition?

Some observers have reasoned that the above deposits were deposited contemporaneously with the other strata; while others, finding evidence of the concentration of the ores especially along fault-planes and other water-channels, have believed that the metals were introduced from extraneous sources through these channels, and are only in bed form because the layers of organic material served to precipitate the metals in the ascending waters. The present writer believes that the theory of original precipitation contemporaneously with the strata has strong features to recommend it, even though he regards a later concentration by circulating waters as proven in many cases.

If these bedded deposits are even in part original, where did the metals come from, and how were they precipitated?

Organic matter is known to be a powerful precipitant of metals from solution. Metals are known to exist in sea-water, even gold. According to Phillips,† the waters of the Mediterranean contain one centigram of copper to the cubic meter. The same writer remarks that the "black and usually very sulphurous matter deposited in basins

* 'Ore Deposits of the United States and Canada.' Fourth Edition, p. 223.
† 'Ore Deposits,' Second Edition, p. 132.

where sea-water has been left to itself constantly contains copper, and the same is generally true with regard to the dark-colored gypseous muds of all ages." Luther Wagoner* found that mud from San Francisco Bay contained gold and silver; and that samples rich in organic matter contained more than at other places. He concluded that organic matter in mud reduces some silver from the sea-water, and probably some gold.

Example: In the Sierra Oscura, New Mexico, are red sandstones and shales of probably Permian age. Some of these red sandstone beds contain copper for an extent of a number of miles. In a certain portion of the region there are at least three distinct copper-bearing sandstones, in which the ore is chalcocite and copper carbonate, disseminated in minute grains. No dikes or igneous rocks of any kind have been found associated with the copper-reefs or the enclosing beds. They do not occupy lines of faulting; and, indeed, were certainly formed before the main faults of the district. The mode of occurrence of the ore in regular beds, in part replacing plant remains, suggests that the copper was deposited from the waters which deposited the enclosing sediments.†

How can one explain the hypothesis that certain geologic periods were more favorable for this process than others?

It may well be that during periods like the Permian and Triassic, where the presence of great land-locked evaporating shallow seas is shown by beds of gypsum, salt, etc., with impure red sandstones, the precipitation of metals in

* *Transactions* American Institute Mining Engineers, Vol. XXXI p. 807.

† H. W. Turner, *Transactions* American Institute Mining Engineers, Oct., 1902.

the muds was greater than at other times. In the first place, the evaporation of the sea-water would concentrate the metals, along with the other substances in solution; in the second place, the shore-line conditions would furnish beds rich in organic matter, for the reduction and precipitation of these metals.

SELECTION OF FAVORABLE STRATA FOR THE SUBSEQUENT DEPOSITION OF ORES.

Subsequent bedded deposits, where the minerals were introduced after the formation of the rocks, show frequently a preference for one kind of rock.

Do sandstones especially attract the precipitation of ores?

Porous sandstones afford channels for waters, and many tiny cavities which may be filled with precipitated minerals; hence they are often selected for ore-deposition in preference to adjoining strata.

Do schists especially attract the deposition of ores?

Schists are often selected for impregnation with valuable minerals for the same reasons as sandstones; moreover, shales, slates and schists containing organic matter often act as precipitants to ore-bearing solutions, and hence become the seat of ore-deposition in preference to other beds.

Example: A small basin of coal-shales, near Belleville, Jasper county, Missouri, carries beautifully preserved fossil plants. The outer surface of the mass of shales, for a

depth of about a foot, contains scattered crystals of blende, with some galena and pyrite. The central portion does not carry any mineral, the mass having been mineralized from the outside, toward the interior, so far only as the mineral-bearing waters could penetrate the dense plastic clay. The crystals in their growth, have distorted otherwise perfect fossil plants, giving evidence that the deposition of the minerals was of later date than the embedding of the plant remains.*

How does a stratum impervious to water cause the precipitation of ores in bedded form?

A porous stratum may absorb the waters coming to it from transverse fissures or other channels, may spread these waters out, make their circulation sluggish, and so induce the precipitation of ores. An impermeable stratum, such as a bed of shale, may refuse all passage to solutions, and compel them to slacken and spread out on its upper or under side (according to whether the waters are ascending or descending), and likewise bring about precipitation.

Example: In a series of interbedded sandstones and shales at Rico, Colorado, occurs a bed relatively impervious to water—the so-called "blanket" (Fig. 4). In the case of the Enterprise mine, the blanket seems to have been formed from the fine residue left from the dissolution of a gypsum stratum, together with a breccia made by the collapse of the overlying beds, as the gypsum disappeared. The rocks have been seamed by nearly vertical fissures, and mineralizing solutions rising along these have been

* W. P. Jenney, *Transactions* American Institute Mining Engineers, Oct., 1902, p. 25.

checked by the blanket, and have deposited their ores in it, on its under side. The ore-deposits, therefore, have a constant relation to this particular bed, but the association is a subsequent one, the ores having been introduced after the deposition of the sediments.

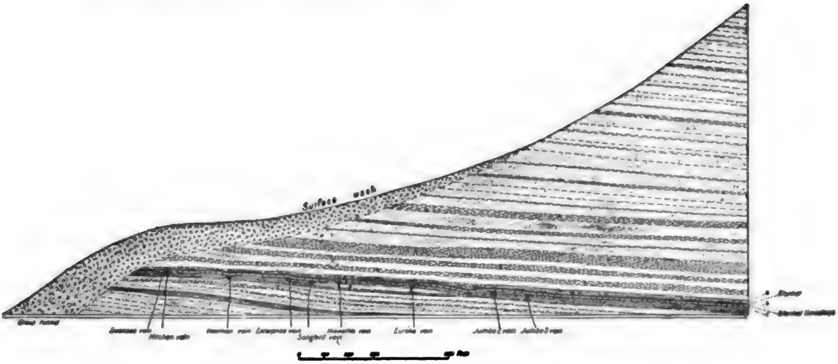

Fig. 4. Longitudinal section through the Group tunnel, Enterprise mine, Rico, Colo. After F. L. Ransome.

Why may ores be deposited in a rigid stratum in preference to soft strata?

A certain stratum may, on account of its rigidity, be favorable to the formation of open fractures, which cease in neighboring soft beds. Hence veins formed along such fractures may be confined chiefly to the more rigid strata.

Why is it that subsequent ore-deposits frequently show a preference for limestones over associated rocks?

Limestone lends itself readily to the process of cavity-making by the dissolving action of waters, more than any other rock, and these cavities are sometimes filled up by minerals. Yet true cave deposits are probably much rarer than they were formerly thought to be. At Eureka, in

Nevada, rich ores occur in caves, but it seems that the caves have been formed by the shrinkage of ore-bodies, attendant upon their alteration.

Limestone is easily replaced by metallic minerals, and for this reason is frequently chosen above other rocks, by circulating waters, as a locus for the precipitation of the metals they carry. Silver-lead deposits, especially, prefer limestone. Iron deposits also frequently choose this rock.

Example: The superior suitability of limestones over other rocks for replacement deposits, particularly of lead, is shown in the case of the Derbyshire lead mines in England. In this district there occur, in limestone, intrusive sheets of igneous rock. Fractures traverse both limestone and intrusive rock, and these fractures, together with the joints and the bedding planes of the limestones, have evidently furnished the channels along which the ore-bearing solutions have circulated. The galena which constitutes the ore, however, has been deposited only in the limestone, and in the intrusive rock the fractures are barren. (Fig. 5.)

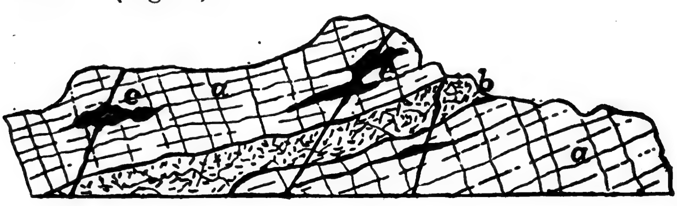

Fig. 5. Lead deposits, Derbyshire, England. After De La Beche. a.=limestone; b.=igneous rock; c.=ore.

How may the chemical peculiarities of certain strata induce the precipitation of ores in them?

Besides the chemical suitability of limestone for replace-

ment, and the precipitating action of beds containing organic matter, other peculiarities of certain stratified rocks may induce ore-deposition.

In shale beds there is always a considerable percentage of iron. This usually combines with sulphur contained in organic matter to form sulphide of iron (pyrite). Pyrite has been shown by experiment to be active in causing other metallic minerals, especially gold, to precipitate.

Example: At Ballarat, in Australia, there are certain thin beds of slate containing pyrite. These are called "indicators,"* for, whenever the auriferous quartz veins of the district intersect them, the veins become uniformly rich, even though in the remainder of their course they will not repay working. The recognition and tracing out of these indicator beds, therefore, becomes, perhaps, the most important geologic work for mining men in these districts. Even when the beds have been bent and broken by earth movements their effect upon traversing lodes is the same.

In sum, then, what sedimentary rocks are most likely to become the site of ore-deposition from circulating waters?

Among the stratified rocks, now one, now another, may by its peculiarities induce its selection in preference to adjoining strata, as a site of ore-deposition. The problem admits of no empirical solution, but in each individual case a comparison of the physical and chemical features of each bed present may aid in deciding which is most favorable,

* T. A. Rickard. 'The Indicator Vein, Ballarat, Australia.' *Transactions* American Institute Mining Engineers, Vol. XXX, pp. 1004-1019.

and in discovering the main mineral belt. Shale beds containing organic matter (especially if the beds be limy and so easily adapted to the process of replacement) offer perhaps the most favorable situation for ores. Next in order comes limestones, while conglomerates are in general not so favorable. Quartzites are the least favorable of all, although even here ore-bodies are not infrequent.

CHAPTER III.

THE STUDY OF IGNEOUS ROCKS AS APPLIED TO MINING.

PHYSICAL CHARACTERS OF IGNEOUS ROCKS.

What is an igneous rock?

A rock is an aggregate of minerals.

An igneous rock is one that has cooled from a molten condition.

How can one tell if a rock is igneous or not?

An igneous rock bears marks indicating its origin, just as the stratified and sedimentary rocks do. In the first place, since igneous rocks were not deposited in successive layers in water, there is no true stratification.

Do igneous rocks never have a banded structure?

In the case of lavas, when one flow after the other is poured out, the accumulated rocks will be definitely layered, for between each flow there may be fragmental broken material. Each flow also may, perhaps, differ slightly in texture and composition from the earlier and the later flows, and within itself the top and bottom will generally be finer grained than the center, on account of having

cooled more quickly. When an igneous rock flows in a viscous, only incompletely molten condition, as it frequently does, it may be drawn out into long bands differing more or less from one another in structure, texture and composition. These bands may be a fraction of an inch or many feet in thickness. This structure is flow-banding.

Does the crystalline structure afford a test for igneous rocks?

The structure of the igneous rock, when closely examined, is the best test of its origin. In the first place, it is usually crystalline. On hardening from a molten or otherwise fluid condition solid substances tend to assume the beautiful and often highly complicated geometric forms which are peculiar to them. In the molten state all the elements are intimately mingled—as consolidation commences they begin to group themselves together according to their affinities, and to form certain combinations which we call minerals, each having a crystal form mathematically distinct from that of unlike minerals.

Are all igneous rocks thus made up of crystalline minerals?

If the consolidation is extremely sudden, this crystallization has not time to take place (at least we cannot detect it, even with a microscope), or is shown only by beautiful groupings of the rock materials, with no definite separation into minerals. The rock, thus quickly hardened, is termed *volcanic glass* or *obsidian.*

Example: Obsidian cliff, in the Yellowstone National Park, rises in nearly vertical walls for 150 or 200 feet. It

has been formed as a surface flow, and is a natural glass, the result of rapid cooling of a fused mass of rhyolitic lava. This glass covers an area of about 10 square miles.*

Is this glassy condition of igneous rocks usual?

Nearly always the cooling is slow enough, even in the case of lavas suddenly poured out, to allow at least the beginning of crystallization. If the period of cooling is relatively short, the crystals will be small in size, sometimes only perceptible with a microscope; if it is slower, the crystals grow till they are very easily visible to the naked eye.

How does one study an igneous rock, to distinguish it from sedimentary and metamorphic ones?

When one observes such a rock, he observes its compact texture (one crystal fitting into another without loss of space); he notes the straight sharp geometric outlines of some of the crystals (whose forms have not been interfered with by intergrowths with neighboring crystals), in distinction to the rounded or broken outlines of the grains of the sedimentary rock. He observes, also, that in general the more prominent crystals do not have any common direction of elongation; that is, they are not parallel with one another, as are usually the crystals of metamorphic rocks, but lie in all possible positions.

Can one always readily distinguish igneous rocks by this test?

There are exceptions to this rule, and in the field the

* Arnold Hague, 'Geological Excursion to the Rocky Mountains,' p. 350.

observer will meet difficult cases. In some hardened rocks where the individual grains are not visible to the naked eye, it may be hard to decide as to the origin, without a microscope. There are, also, cases of igneous rocks where there is a general parallelism of the crystals, though never on so complete a scale as in metamorphic rocks. In the cases referred to, the crystals, originally not parallel, have been so arranged by flowage.

THE DIFFERENT KINDS OF IGNEOUS ROCKS.

How are igneous rocks classified?

Igneous rocks have been named in various ways, according to various classifications. All these classifications are more or less artificial, and each worker must select the one which serves his purpose best. Various features have served as main distinctions—chemical composition, mineral composition, form, structure, geologic age, mode of occurrence, locality, etc. For one purpose a chemical classification may be best, for another a classification as to mode of occurrence, etc. The commonly accepted classification is based partly on mineral composition, partly on chemical composition, and partly on structure.

How are the different kinds of igneous rocks studied and identified?

Since the adaptation of the microscope to petrographic work, the science has been revolutionized; and now all the real study is done with that instrument. As a result of the detailed investigation thus made possible, the distinctions

have in many cases been finely drawn, and the number of rock names has rapidly multiplied.

Is it an easy thing to name an igneous rock correctly in the field?

Petrologists very commonly have difficulty in defining a given igneous rock, without resource to their microscope. To take lava-rocks, for example, one cannot always decide without the microscope between many varieties of rhyolite, phonolite, trachyte and andesite. The same is true of the dike rocks, which have received a great number of special names, now falling into disuse. In coarse-grained rocks, the petrologist can be more certain, yet it sometimes becomes difficult in the field to distinguish certain kinds of granites, syenites and diorites from one another, and to decide between some diorites and diabases.

CLASSIFICATION OF IGNEOUS ROCKS FOR MINING MEN.

To what extent is it possible and necessary for the miner to classify igneous rocks?

When such is the case, it is plain that the fine distinctions of rock species are beyond the mining engineer and the miner. Luckily, such distinctions, even could he make them, would be of slight use to him. But broad demarcations are necessary, and may be made upon physical characteristics, without the microscope and chemical analysis, and with only a slight knowledge of mineralogy.

On what principles is such a practical classification based?

The classification the writer offers for this purpose is based on: (1) Structure. (2) Mineralogical composition. Rocks are first divided into granular, coarse porphyritic, fine porphyritic, and glassy forms.

What is meant by a granular igneous rock?

The term granular is applied to a fairly even texture, the constituent minerals being of nearly uniform size, and generally interlocking.

What is meant by a porphyritic igneous rock?

Porphyritic rocks do not have their constituent minerals of uniform size. There is a fine grained portion, which may be dense and show no crystals to the naked eye, or may sometimes be non-crystalline, like glass. This is the *groundmass.* Through it are sprinkled crystals of larger size, generally with perfect geometric outline, and often separated from one another. so as to be completely surrounded by the groundmass. These are *porphyritic crystals* or *phenocrysts,* and the rock possesses *porphyritic structure.*

In the coarse porphyritic structure, the groundmass is crystalline, the individual minerals in it are usually visible to the naked eye, or by the aid of a hand-lens, and the porphyritic crystals are correspondingly large. In the fine, porphyritic structure, the groundmass is fine, the individual grains being difficultly or not at all discernible to the naked eye; or it may be glassy.

What is meant by a glassy igneous rock?

Glassy rocks have no or few porphyritic crystals; neither do they show any grains, even under the microscope—they are smooth and homogeneous, like glass.

What is the relative abundance of these different kinds of rock?

Granular rocks, coarse porphyritic and fine porphyritic rocks are common; wholly glassy rocks are relatively rare, and are found chiefly among the outpourings of volcanoes.

Classification of Igneous Rocks.

A. Granular Rocks. Relatively coarse; crystals of constituent minerals easily visible to the naked eye, and all of about the same size.

1. *Granitic Rocks.* Color gray, reddish or greenish. Relatively light in color and weight. Quartz abundant, while dark minerals (hornblende, mica, pyroxene, etc.) form only a small portion of the rock. Mica apt to be more abundant than in other granular rocks. Forms of mineral grains in general short and blunt. Chief constituent minerals, quartz, feldspar, mica, hornblende.

2. *Dioritic Rocks.* Of medium dark color and medium weight; mottled, generally green, rocks. Quartz scarce or absent; dark minerals (especially hornblende) fairly abundant. Mica may be present, but is generally less in amount than other dark minerals. Pyroxene may occur. Grains of individual minerals have a tendency to elongated forms, though they may be short. Constituent minerals, feldspar, hornblende, mica.

3. *Diabasic Rocks.* Very dark and heavy, green of

various shades, often black. No quartz, and very large proportion of dark minerals. Mica almost always absent. Pyroxene is usually very abundant, and there is often olivine and hornblende. Magnetite in small grains (usually invisible to the naked eye) is nearly always present. Crystal forms generally elongated. Chief constituent minerals, feldspar, pyroxene, olivine.

4. *Peridotitic Rocks.* Color, very dark green or black, darker and heavier than any of the foregoing. Are distinguished by the absence of feldspar. Often contain considerable quantities of the metallic minerals (such as magnetite, pyrrhotite, ilmenite, etc.) in small grains. Chief constituent minerals, olivine, pyroxene, and hornblende. Any one of these, or any two, may in some cases be entirely lacking, leaving the rock composed essentially of two of the above-named minerals, or even one.

B COARSE PORPHYRITIC ROCKS. Are spotted with well-formed crystals of the common rock-forming minerals, quartz, feldspar, mica, hornblende, pyroxene, etc., which are contained in a groundmass composed of interlocking crystals of markedly smaller size than the porphyritic crystals.

1. *Granitic Porphyry.* Combines the coarse porphyritic structure with the same physical and mineralogical characters as the granitic rocks, as defined above. Chief constituent minerals, quartz, feldspar, mica, hornblende.

2. *Dioritic Porphyry.* Combines the coarse porphyritic structure with the same physical and mineralogical characters as the dioritic rocks, as described above. Chief constituent minerals, feldspar, hornblende, mica.

3. *Diabasic Porphyry.* Combines the coarse porphyritic structure with the same physical and mineralogical characters as diabasic rocks, as described above. Chief constituent minerals, feldspar, pyroxene, olivine.

C. Fine Porphyritic Rocks. Like the coarse porphyritic rocks, but the groundmass is finer, so that the individual crystalline grains in it are barely or not at all visible to the naked eye.

1. *Rhyolitic Rocks.* These are chemically and mineralogically the same as the granitic rocks and the granitic porphyry rocks, but differ in having the fine porphyritic structure. Rhyolitic rocks are generally of light color (white, light gray, pink, red, etc.) and of relatively light weight. As porphyritic crystals they generally show quartz, hexagonal in cross-section, and frequently short, blunt feldspar. Crystals of dark mica are usual, and often also hornblende; but the amount of dark minerals is relatively small. The groundmass is generally rather rough to the touch, and looks and feels somewhat like broken coarse earthenware; the individual grains in it are usually not distinguishable. Chief constituent minerals, quartz, feldspar, mica, hornblende.

2. *Andesitic Rocks.* These are chemically and mineralogically the same as the dioritic rocks and the dioritic porphyry rocks, but differ in having the fine porphyritic structure. In color the andesitic rocks are dark gray, medium brown, dark red, etc. They are of medium weight. Quartz is usually not found as porphyritic crystals, and mica is not as common as in rhyolitic rocks. The porphyritic crystals are most apt to be feldspar and hornblende, often pyroxene. Dark minerals in general are rather abundant. Groundmass generally slightly coarser than with the rhyolitic rocks; the individual grains, though they may be tiny, are often visible either to the naked eye or through a hand-lens. Chief constituent minerals, feldspar, hornblende, pyroxene, mica.

3. *Basaltic Rocks.* These are chemically and mineralogically the same as the diabasic rocks, and the diabasic

porphyry rocks, but differ from them in having the fine porphyritic structure. The porphyritic crystals are generally few, and do not differ so markedly in size from the groundmass crystals as in the rhyolitic rocks and the andesitic rocks. The groundmass is generally coarser than in the andesitic and rhyolitic rocks; the individual grains in it, though fine, can often be seen by the naked eye. If they cannot, there are very likely no porphyritic crystals to be seen. Basalts contain as a rule no quartz or mica. They are usually black in color and heavy. Where minerals can be distinguished in them, they are usually pyroxene, feldspar, or olivine. Chief constituent minerals, feldspar, pyroxene, olivine.

ADDITIONAL DEFINITIONS.

Does this classification embrace all the rock names necessary to a miner?

In the writer's opinion, this is about as far as one who is not a petrologist can safely go. There are, however, other rock names frequently used by miners, on which observations will be made.

What is quartz porphyry?

This is familiar to mining men as one of the most important rocks in Leadville and other mining regions. The name, formerly in good use by geologists, is being dropped for granite porphyry or rhyolite porphyry, the former for the coarse grained, the latter for the finer grained varieties. The description of granite porphyry is that of quartz porphyry.

What is syenite?

This is a favorite term with miners. A syenite is a granite without quartz. Like granite, it has a light color and relatively light weight, contains relatively small amounts of the dark-colored minerals, and is apt to contain mica. It is not always easy to distinguish syenite from diorite in hand specimens. Syenites are comparatively rare rocks.

What is trachyte?

Trachyte was formerly a much-used term with geologists. In the Great Basin of Nevada, for example, enormous quantities of volcanic rocks were classified as trachyte. Now microscopic study has shown them to be mainly andesites, and that none of them are trachytes. Trachyte is still a popular term with miners, but now we know it to be a comparatively rare rock. True trachyte bears the same relation to syenite as rhyolite does to granite; it has the chemical and mineralogical composition of syenite, but with the fine porphyritic structure. It is, therefore, a rhyolite without quartz.

What is phonolite?

Since this rock occurs in connection with the famous gold ores of Cripple Creek, in Colorado, it has become well known in the mining world. It is often difficult to identify phonolite without microscopical or chemical tests. Phonolite contains, besides feldspar, nepheline, leucite, or both, and pyroxene, sometimes hornblende. The colors are

usually gray or green. Phonolites are also relatively rare rocks.

It is popularly supposed that the metallic ring emitted by fragments of some volcanic rocks is a test for phonolite; but this is an antiquated idea. Rhyolites and other rocks frequently give this ring.

What is amygdaloid?

Amygdaloid is a term applied to lavas which are cellular, that is, are full of little holes or amygdules, which were filled by steam at the time of consolidation. In the Lake Superior region certain amygdaloidal basalts have their amygdules filled with native copper, and so become ores and of considerable interest to the miner.

What is dolerite?

Dolerite is a term that has been used, sometimes instead of diabase, sometimes instead of basalt.

What is gabbro?

The term gabbro is applied to certain granular rocks consisting chiefly of feldspar and pyroxene. It thus falls within the group of diabasic rocks, in the foregoing classification.

What is felsite?

Felsite is a general term applied to certain light-colored, very fine-grained igneous rocks, chiefly altered rhyolites. Strictly speaking, felsite is hardly an accurate term, and most rocks so called may be proved to be rhyolite or

rhyolite porphyry. In felsites the porphyritic crystals are small and few, or have become inconspicuous on account of decomposition, and so are not visible to the naked eye. The term is an allowable one, and, on account of its broad definition, not difficult of application.

Example: Study of the felsites of Carodoc, Wales, show microscopic structures which had been altered almost beyond recognition, but which indicate that these rocks were originally partly rhyolites and partly sedimentary beds derived from the erosion of rhyolites (rhyolite tuffs).*

What is greenstone?

Greenstone is a general name applied to certain igneous rocks, generally rather fine-grained, of a general dark green color. The term is used by geologists, especially when no more accurate definition is possible in the field. The greenstones are usually old rocks geologically, and the green color is the result of thorough alteration. They are diabases or diorites, sometimes old andesites and basalts. The term is admissible and of easy application.

Example: In northeastern Minnesota, on the eastern part of the Mesabi iron range, are rocks which have been called greenstones because of their general dark greenish color. They are crystalline rocks composed usually of hornblende and feldspar. Mineralogically, the rocks are diorites, but they have been recrystallized from other rocks, some of which were certainly diabases and andesites and some probably diorites or gabbros.†

* F. Rutley, *Quarterly Journal*, Geological Society, Vol. XLVII, p. 512.
† U. S. Grant, 'Engineer's Year Book,' University of Minnesota, 1898, p. 54.

What is pegmatite or giant granite?

Pegmatite or giant granite is a name applied to those common dikes, generally granitic, where the grain is exceedingly coarse, individual crystals being frequently several inches across.

What is serpentine rock?

This is a rock consisting partly or wholly of the dark-green, greasy-feeling mineral serpentine. It is a metamorphic or altered rock, and in many cases is derived from igneous, chiefly peridotitic rocks. The decomposition of the olivine and pyroxene of peridotites usually affords serpentine.

What is trap?

Trap is an old general name for dense, dark-colored dike rocks. The term is still in use. A trap dike, more accurately considered, may be made up of andesite, basalt, diorite or diabase, etc.

What is breccia? *

Breccia is an Italian word, applied to crushed and broken, yet still consolidated rock. A breccia resembles a conglomerate in being composed of coarse fragments packed together; but in the former the pieces are sharp and angular, in the latter rounded by water action, indicating their origin. It is generally easy to recognize a breccia, but sometimes it is difficult to tell how it originated. Where there has been movement in a rock, as along the vicinity of

* Pronounced brék-she-ah, with accent on the first syllable.

a fault, a breccia is developed, called a *friction breccia.* Lava, on the other hand, is often shattered by explosion attending its eruption or by being forced into renewed movement when partially hardened. The result is a *volcanic breccia.*

What is pumice?

Pumice is a glassy lava, which at the time of hardening was so full of steam-filled cavities that it now has a spongy structure, and is so light that it often floats: it is a sort of lava froth.

TRANSITIONS BETWEEN DIFFERENT KINDS OF IGNEOUS ROCKS.

Are the divisions of igneous rocks, as given, sharply divided from one another in point of mineralogical composition?

Igneous rocks form a connected series, with gradual transitions from one of the artificial divisions above outlined to the other. This is the case in any classification. No matter how many divisions are made, some rocks will be found occupying the border lines. So it is very possible, for example, to classify a rock in the field as a diorite. which closer study would show to be a diabase. The suffix "ic," as diorit-ic, in the foregoing scheme, expresses a provisional determination, and saves one from the charge of making hasty and faulty decisions.

Are the different igneous rocks separated sharply in point of texture?

In point of texture there are all transitions between

granitic rocks, granitic porphyry rocks, and rhyolitic rocks; also between dioritic rocks, dioritic porphyry rocks and andesitic rocks; and, again, between diabasic rocks, diabasic porphyry rocks and basaltic rocks; in short, between granular rocks, coarse porphyritic rocks, and fine porphyritic rocks.

How did these different textures originate?

The difference in general seems to depend on the rapidity with which the rock cooled, those which cooled more slowly having had more time to crystallize, and hence producing larger crystals and coarser rock texture. The rapidity of cooling depends in large part on proximity to the surface. Those which cool at the surface chill quickly; while those that harden deep in the earth's crust retain their heat for a long time. Therefore it is that the lavas or surface rocks are almost wholly of fine porphyritic structure. Small masses of molten rock thrust into older harder rocks and there cooling (dikes), generally have the coarse porphyritic structure, though often the fine porphyritic. Large masses of rock cooling at a distance from the earth's surface have generally the granular structure. Cases may occur where a rock mass may be fine porphyritic on the edges, where it cooled quickly, coarse porphyritic further in, and granular in the center, but in general rocks are more or less homogeneous.

Are the different igneous rocks sharply separated in point of composition?

Similarly, a single rock mass may vary in composition, so

that, for example, it is a diabase on the borders and a diorite in the center; yet usually the different types of rock are distinct in the field.

Example. The exceptional occurrence of different rock-types as part of a single dike is shown at a locality in Michigan, near Crystal Falls. Here, there has been observed a dike, four feet wide, which cuts a mass of gabbro. Near the center of the dike the rock is a granite, containing biotite, while the sides consist of diorite without any quartz. The two rocks are supposed to have separated one from another while the mass was in a molten state.*

FORMS OF IGNEOUS ROCKS.

In what different forms do masses of igneous rocks occur?

The forms in which igneous rocks occur may be outlined thus:

1. Fundamental.
2. Intrusive (Masses, dikes, sills or sheets.)
3. Extrusive. (Lavas.)

What are the fundamental igneous rocks and what is their origin?

The fundamental igneous rocks underlie the oldest stratified rocks. They are mostly Archæan granites and form the floor on which the first recognizable sediments were laid down. Many of them may be metamorphosed and crystallized early sediments.

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* J. M. Clements, *Journal Geology*, Vol. IV, No. 4, p. 377.

What are intrusive rocks?

In the molten rocks, which exist below or within the crust of the earth, important movements and migrations occur. The plastic material is propelled upward by the steam which it contains and by other causes, and so forces its way into and through the hard rocks nearer the surface. It enters these rocks along the line of least resistance—along fissures, fault-planes, joints, crushed zones, or bedding planes.

What is an intrusive mass?

The molten rock may come up in large volume, thrusting aside or absorbing the rocks it enters (the intruded rock), and thus forming a mass of irregular shape.

What is a dike of igneous rock?

Where the molten rock ascends along fissures or other similar channels, it will form a zone, or a body with very slight thickness as compared with its extent in other directions. In form, a dike has the same characters as a vein. Its boundaries are generally straight planes, and it may dip away from the horizontal at all possible angles. A dike may be an inch or a mile across, but it is usually vastly longer than it is thick. (Fig. 6.) From a great mass of intrusive rock there are usually smaller dikes which run out into the surrounding formations.

What are sheets or sills of intrusive rock?

In a sedimentary rock, when the dikes run along the bedding planes, and so are parallel, or nearly so, to the

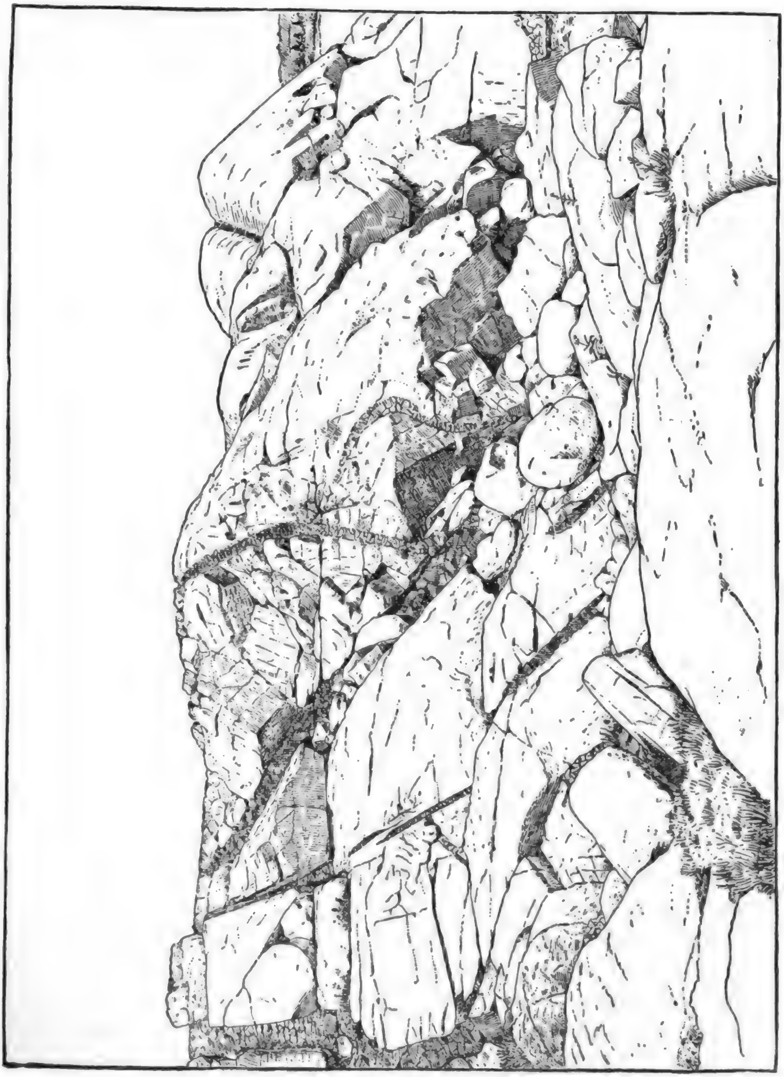

Fig. 6. Dark-colored dikes cutting granite. Cape Ann, Massachusetts. After N. S. Shaler; 9th Annual Report United States Geological Survey.

stratification, they are called sheets or sills. A sheet or sill may be thick or thin; there sometimes may be many of them, alternating with beds of sedimentary rock.

How is it that we find fundamental and intrusive igneous rocks at the earth's surface?

Although fundamental and intrusive rocks were originally far below the surface, yet by the long process of erosion the overlying mass has been stripped off and these rocks are exposed to the light of day. That is why we now find them at the surface as often as we do those which were poured out of volcanoes.

What are extrusive rocks or lavas?

Extrusive rocks are those which reach the surface by means of the conduits above mentioned, and overflow either from volcanoes, as explosive eruptions, with ashes and scoriæ, or as quiet wellings-out, either from volcanoes or fissures. Beneath the surface are dikes which have been the feeders, and the same lava may have spread out along the bedding planes of the stratified rocks as sheets or sills.

Example: Examples of the pouring out of lavas from volcanoes, with attendant showers of ash, pumice, etc., are too well known to require specific mention.

An instance of the quiet welling out of a great mass of lava along fissures is furnished by the Columbia river basalt, which covers a great arid plain in Idaho, Oregon and Washington. This lava consists of a series of flows from 20 to 150 feet thick, piled one on top of another. The dikes which were the feeders to the flows are now in part exposed in Oregon, by the erosion of the overlying rock;

and the lack of any ash or fragmental material, or volcanic cones, shows that the eruption was quiet.* In Idaho a total thickness of as much as 5,000 feet of this basalt is shown by the Snake River cañon, which has cut down through it. Before the eruption of the lava there was in this region a varied topography, but the mountain ranges, deep valleys, and cañons were all blotted out by the swiftly succeeding flows, until only the very highest peaks still show their heads.†

GENERAL RELATION BETWEEN IGNEOUS ROCKS AND ORE-DEPOSITS.

Is there any relation between igneous rocks and ore-deposits?

There is the very closest connection. Probably nine out of ten ore-deposits have some visible relation to a body of igneous rocks. In general, also, a country free from igneous rocks has a scarcity of ore-deposits.

What is the reason for this relation?

The reasons for this are, in part at least, known. All igneous rocks contain metals. Iron, for example, is present in every igneous rock in large amount—the percentage of the whole rock being in some diabases and basalts 15 or 20 per cent., or even more. Manganese, also, is present in most igneous rocks in noticeable quantities. When we come to the rarer metals, we naturally do not find them in such amounts; but chemists have proved the presence of

* W. Lindgren, 22d Annual Report United States Geological Survey, Part II, p. 741.

† W. Lindgren, 20th Annual Report United States Geological Survey, Part III, pp. 91, 93.

such metals as copper, lead, zinc, nickel, tin, etc., in nearly every kind of igneous rock. These metals usually occur as constituents of the dark-colored silicates (hornblende, pyroxene, dark mica, olivine, etc.) Even the rarest, such as silver, platinum and gold, are similarly found, though in small quantities.

Do metals occur in igneous rocks except as constituents of the dark-colored silicates?

The commoner metals occur in igneous rocks in the same form that they do in ore-deposits—in the form of sulphides and oxides. This has been proved in the case of iron pyrite, the magnetic sulphide of iron (pyrrhotite), the magnetic oxide of iron (magnetite), the magnetic oxide of iron with titanium (ilmenite or titanic iron), the oxide of iron and chromium (chromite), etc.

Example: In the diabase rocks of the Grass Valley district, California, there are small, very abundant grains of pyrite, pyrrhotite, and ilmenite, which occur within the augite and feldspar of the rocks in such a way as to prove that the metallic minerals are of primary origin (that is, that they have crystallized out of the cooling molten rock, and have not been introduced subsequent to its consolidation), and indeed were the first of the rock-forming minerals to solidify. (Fig. 7.)

Do not the sedimentary rocks also contain disseminated metals?

Chemical investigation seems to bear out the statement that as a rule the sedimentary rocks, although they also

contain small quantities of the metals, yet are relatively poorer in these than the igneous rocks.

Example: Mr. Luther Wagoner* has made a series of delicate determinations of gold and silver in certain igneous and sedimentary rocks of California. Four specimens of granite showed respectively the following weights in milligrams per ton: gold, 104, 137, 115, 1130; silver, 7660, 1220;

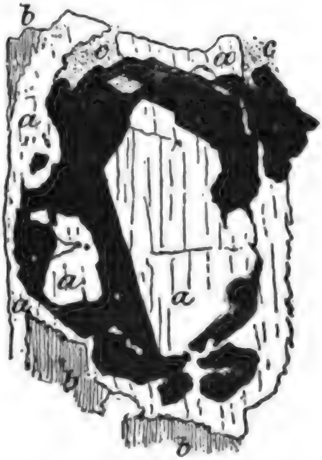

Fig. 7. Primary pyrrhotite in augite. Black, pyrrhotite; a. augite; b. uralite;† c. chlorite. From W. Lindgren; 17th Annual Report United States Geological Survey, Part II.

940; 5590. One specimen of syenite contained gold, 720; silver, 15,430. A specimen of diabase contained gold, 76; silver, 7,440. One of the basalt gave gold, 26; silver, 547.

The sedimentary rocks tested were three specimens of sandstone and two of marble (one of the latter from Italy). The sandstones gave respectively in gold, 39, 24, and 21; in

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* 'Detection and Estimation of Gold and Silver.' *Transactions* American Institute Mining Engineers, Vol. XXX, p. 793.

† A variety of hornblende.

silver, 540, 450, 320. The California marble showed gold, 5; silver, 212; the Italian sample, gold, 8.63; silver, 201. Several assays in San Francisco Bay mud (containing some organic material) gave gold, from 45 to 125. Two assays of sea-water gave a mean gold 11.1; silver, 169.5 milligrams per ton.

On the average, therefore, the granite contained 371 milligrams gold and 3852 silver; while, as before stated, the syenite contained 720 gold and 15,430 silver; the diabase 76 gold and 7440 silver; and the basalt 26 gold and 547 silver. Taking the sedimentary rocks, the sandstones averaged 28 gold and 437 silver; the marble, 7 gold and 206 silver; and the bay mud 85 gold.

Averaging the igneous rocks assayed, we find a mean of gold 330 and silver 5547, while the mean of the sedimentary rocks (sandstones and marbles) is 17 gold and 344 silver. That is to say, the mean of the igneous rocks assayed contains about 19 times as much gold and 16 times as much silver as the mean of the sedimentary rocks.

Are disseminated metals equally abundant in different kinds of sedimentary rocks?

In regard to the sedimentary rocks, it will be noticed that the sandstones in these tests contained on an average four times as much gold, and over twice as much silver as the marbles; while the bay mud (which in hardening would become shale) contained nearly 13 times as much as the marble.

Are disseminated metals equally abundant in different kinds of igneous rocks?

As regards the igneous rocks, if we take the silicious or acid rocks (granite and syenite) thus examined and compare

their mean with that given of the basic rocks (diabase and basalt), we find that the silicious rocks showed nearly nine times as much gold and about one and a half times as much silver as the basic ones. It remains to be seen whether further data would confirm these results.

What bearing has the presence of disseminated metals in igneous rocks on the question of the relation between igneous rocks and ore-deposits?

The metals disseminated in igneous rocks often become concentrated by various agencies.

Is there no other reason for this relation?

There is another reason, and one perhaps as important, why ore-deposits are so closely connected with igneous rocks. These rocks retain their heat a long time before cooling. In the case of rocks that cool beneath the earth's surface, it is safe to say that they keep their heat for centuries of centuries. So all circulating waters passing through them become heated, and the hot water having less specific gravity than cold water (water expands on heating) has a tendency to rise, and to appear at the surface as hot springs. This hot water has a power of solution—and hence a power of concentrating the disseminated metals (whether in the igneous or in the stratified rocks) into ore-deposits—many times greater than cold waters. There are three phenomena frequently found to be connected: igneous rocks, hot springs and ore-deposits. Often, however, we find districts where the igneous rocks have

long ago cooled, even far beneath the surface, and where there are ancient ore-deposits, but no longer hot springs.

Is the presence of hot springs favorable to the finding of ore-deposits?

The presence of hot springs in a country is favorable to ore-deposits; but their absence cannot be taken as a sign that such deposits do not exist. Hot springs are most likely to occur in regions of younger eruptive rocks (Tertiary, for example), where the under rocks are still hot; and not so often in the older and perfectly chilled rocks.

*How are the disseminated ores of igneous rocks concentrated, before or during cooling?**

While the rock is still partially molten and fluid, the different elements have some power of moving about, and it is usually held that on account of the mutual attraction of like materials they tend to group themselves and form bodies more or less concentrated.

How is the process of magmatic segregation supposed to effect the concentration of basic materials?

During the earlier period of cooling, the metallic sulphides and oxides, which are among the first minerals to crystallize, and are especially abundant in basic† rocks, may collect. In some igneous rocks rich in iron, the iron becomes especially abundant in places and even may be sufficiently

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* The material of the following few pages follows closely certain portions of Chapter I.

† *i. e.* Dark colored, heavy rocks, containing a low percentage of silica.

concentrated to form an ore, though always retaining its character of an original constituent. In Greenland, masses of native iron have been found in basalt. Magnetite, the magnetic oxide of iron, is sometimes sufficiently abundant to form ore-bodies in this way. Such is the case, for example, in Sweden, in Rhode Island, in the Lake Superior region, in Canada and elsewhere.

Example: The titaniferous iron ores (magnetites) of the Adirondack Mountains in New York are associated in all cases with basic igneous rocks, which have been intruded into older gneisses and crystalline limestones. The transition from the basic wall rock (generally gabbro) to ore usually takes place gradually, but within a short space. There is no ore along contacts, nor any evidence of the formation of the ore after the consolidation of the rock. The basic rock itself has been split up by segregation of its essential minerals, so that some portions are almost entirely of feldspar, while other portions contain large amounts of pyroxene (making a gabbro). It is plain that the magnetite which forms the ores has been segregated, like the feldspar and pyroxene, while the rock was in a partially molten state; and it is possible that the high specific gravity of the iron may have been influential in bringing about this result.*

Are there other ore-deposits, besides those of iron, which are thus known to be original, and due to magmatic segregation of basic materials in igneous rocks?

The mixture of oxide of chromium and oxide of iron

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* J. F. Kemp, 19th Annual Report United States Geological Survey, Part III, pp. 383-422.

(chromite) is frequently found in tiny crystals in the igneous rocks, and may be so abundant in certain parts that it forms an ore. It may even form solid masses, crowding out the other rock-forming minerals. Many of the known chrome ore-deposits have been held to belong to this class.

Corundum, the oxide of aluminum, used chiefly as an abrasive (the pure varieties are precious stones—sapphire and ruby), has, in a number of cases, been found to be an original constituent in igneous rocks, not only in small quantities, but in those accumulations which are mined as ores.

Nickel is found in fresh igneous rocks as part of a number of minerals. Pyrrhotite, which is a magnetic sulphide of iron, very commonly contains nickel, and is one of the principal ores; it is a not uncommon rock-forming mineral. Large masses of nickeliferous pyrrhotite have been explained by good authorities as original constituents of igneous rocks; but others have questioned these conclusions.

How does the process of magmatic segregation effect the concentration of silicious materials?

During the final stages of consolidation, heated waters, steam and gases (containing silica, with earthy and metallic minerals, in solution), which are left over from the cooling mass, deposit their solid portions in the form of pegmatite or quartz, as nests or veins in the hardening rock or in some neighboring formation. It is held by some that certain of the quartz veins having this origin contain suf-

ficient gold to render them ores; but this conclusion is not yet universally accepted.

Do the residual silicious solutions always form pegmatites and quartz veins?

The residual silicious solutions, instead of forming definite veins, may penetrate the rock with which the cooling igneous mass is in contact, and there may deposit their solid portions, usually by replacement of the original rock.

When the resulting altered rock contains ores, it is called a contact metamorphic deposit.

What are the characteristics of contact metamorphic deposits?

The first mark identifying this class of deposits is their location at the contact of an intrusive igneous rock with another rock, or in evident close relation to it. But this is not sufficient; for other deposits may in some cases be formed along such a contact, circulating waters having found this the easiest channel. In the true contact metamorphic deposit, mineralization has been accomplished by materials pressed out of cooling rock. These materials consist of heated waters and aqueous gas, mingled with other gases of various kinds, and both the escaping waters and the gases may carry in solution metallic and other minerals, which they may deposit near the contact, in concentrated form. Under these conditions certain minerals are characteristically formed which are rare in simple hydatogenic* deposits. Such are minerals like fluorite,

* Water-formed.

tourmaline and topaz, containing the volatile elements boron and fluorine. Garnet is also a rather characteristic mineral of these deposits. According to W. Lindgren,* a characteristic feature is the association of oxides of iron with sulphides.†

Example: The ores at the old Tungsten mine, Trumbull, Connecticut, have been formed at the contact of an igneous rock (now metamorphosed to hornblende gneiss) and a limestone into which the igneous rock was intrusive. The ore occurs on the contact of these two rocks, in beds from 3 to 5 feet thick. It consists of quartz containing iron pyrites, epidote, calcite, mica, and the wolfram minerals (scheelite and wolframite) for which the mine has been worked. Zoisite, garnet, scapolite, hornblende, and marcasite, are also found. This ore-bearing contact zone was due to the action of solutions at the contact of the intruded igneous rock, these solutions being both heated and under pressure.‡

Associated veins are of pegmatite or vein quartz, and contain, besides feldspar, muscovite and other common minerals, topaz in large masses, fluorite, etc.

What are some of the special results of vapors and gases in the residual material under discussion, as regards deep-seated deposits?

The deposits formed by the material expelled from cooling igneous rock probably vary according to the nature and the

* 'Character and Genesis of Certain Contact-Deposits.' *Transactions* American Institute Mining Engineers, Vol. XXXI, p. 227.

† As contemporarily formed minerals.

‡ W. H. Hobbs, 22d Annual Report United States Geological Survey, Part II, p. 13.

relative abundance of the gases. Pegmatites usually show, from the presence of certain minerals containing well-known gases in their composition, the presence and agency of those gases in their formation. Tin-veins and veins containing other valuable minerals, metallic and earthy, are probably often formed largely by the action of abundant gases, escaping from cooling granular rocks, deep below the surface.

What characteristic evidence as to their origin do veins of this class offer?

The characteristic sign of the origin of these veins is the presence of minerals which do not easily form under simple aqueous conditions, but are commonly produced by the action of vapors. Among these minerals are tin-stone (cassiterite, oxide of tin) itself, and others like tourmaline, topaz, etc. Many apatite (phosphate of lime, with fluorine or chlorine) deposits also probably belong to this class, as the presence of the volatile elements (chlorine and fluorine) in the mineral itself indicates. One of the commonest minerals found in association with the apatite, that is, scapolite, bears the same evidence, for the scapolites are minerals whose composition is practically the same as the feldspars, save for the presence of chlorine, indicating the agency of this gas at the time of formation.

Are ores deposited also by vapors and gases escaping from volcanic rocks at or near the surface?

At the surface, orifices emitting vapors and gases from cooling volcanic rocks are termed fumaroles. From these

gases valuable earthy and metallic minerals may be deposited. This fumarolic activity may persist for ages.

Alunite or natural alum (sulphate of aluminum and potash), for example, is formed in commercially valuable quantities by the action of sulphurous gases on igneous rocks containing potash and aluminum. Sulphur, deposited in this way, is actively exploited in Italy and elsewhere. On the walls of fissures in lava, where steam and other gases escape, various metallic minerals have been found which are due to this action, such as specular iron (hematite, oxide of iron), cinnabar (sulphide of mercury), realgar (sulphide of arsenic), etc. Other ores very likely are sometimes formed in this way.

Example: The Bassick mine is in Custer county, Colorado. The rock of the region is gneiss, but an explosive volcano has broken through, producing a pipe which is now filled with rounded boulders, chiefly of volcanic rock. In places these boulders are coated with rich metallic minerals. The first coat consists of lead, antimony, and zinc sulphides; an intermediate coat is of zinc sulphide, rich in silver and gold; other coats are of chalcopyrite (sulphide of copper and iron), and pyrite (sulphide of iron). Tellurides of the precious metals also occur. These ores are very generally considered by geologists to have been brought up in the form of vapor during the fumarolic activity of the volcano.

SPECIAL RELATIONS BETWEEN CERTAIN IGNEOUS ROCKS AND ORE-DEPOSITS.

Advantages of Different Forms of Igneous Rocks.

What especial phases do the processes attendant upon cooling show in fundamental igneous rocks?

Fundamental rocks are generally of coarse grain, showing slow consolidation. Since they have cooled in many cases at great depth, gases and vapors attending this process may have formed characteristic ore-deposits. Tin-veins, for example, are, as noted, generally confined to such rocks, of granitic composition.

What advantages or disadvantages do extrusive rocks possess for ore-concentration?

Extrusive rocks and hot springs are allied occurrences; yet, unless the flows of these rocks are very thick, they are too near the surface for hot-spring action to exercise its best effort in producing mineralization; for the heat of the rocks disappears with comparative rapidity, and with it the great concentrating power of the waters. Where the flows are very thick, however, the central portions remain warm for a very long time, and the hot-spring action is prolonged and becomes more productive of results.

Fumarolic activity, properly speaking, and fumarolic deposits are confined to extrusive rocks; while contact metamorphic deposits are lacking.

What advantages have intrusive rocks over others in bringing about ore-deposition?

Intrusive rocks are the most favorable for promoting the formation of ores. Like all igneous rocks, they contain disseminated metals. On account of their being distant from the surface, they cool with comparative slowness, especially if they are in bodies of considerable size; and thus the conditions for ore concentration are prolonged.

Intrusions come in contact with other igneous rocks and with stratified rocks. While the igneous rocks are better fitted than the sedimentaries for instigating the processes of ore-deposition and for furnishing the disseminated metals to the mineralizing waters, yet the latter are more suitable for precipitating the dissolved metals. This is due to the easy dissolution and replacement of the limestones, to the tiny pores of the sandstones, which permits interstitial deposition, and to the organic matter of the shales, which often acts as a direct precipitant. Hence, where the two classes of igneous and sedimentary rocks are intimately associated, the most favorable conditions are realized.

Advantages of Different Kinds of Igneous Rocks.

Preferences of Certain Igneous Rocks for Certain Ores, Displayed During the Cooling Processes.

Are the dark basic rocks more closely associated with ore-deposits than the light silicious ores?

It has been found by chemists who have investigated the metallic contents of fresh igneous rocks that the metals

were mostly present in the dark "ferro-magnesian" minerals—hornblende, pyroxene, black mica, olivine, etc. This being the case, we might expect ore-deposits to be more definitely associated with the dark-colored basic rocks than with the silicious ones. But this is only partly the case; the preference seems to depend chiefly on the kind of metal.

Are some metals preferentially associated with light-colored and silicious rocks?

Tin is usually found in, or in relation with, granite; and a general close connection with silicious rocks seems the case with tungsten and molybdenum.

Example: In the Malay Peninsula tin deposits are found, mainly on the western slope of the mountain range that forms the backbone of the peninsula. This range is composed largely of granitic rocks, with some limestone and sandstone. The ore is cassiterite, associated with tourmaline, hornblende, tungsten minerals, magnetite, muscovite, topaz, fluorite, sapphire, etc. Veins are found generally in the granite, less frequently in the other rocks.*

Are some metals associated by preference with dark-colored and basic rocks?

Chromium ore-deposits (chromite), for example, are hardly found save in very basic rocks—peridotites.

When these peridotitic rocks decompose, they become serpentine, which accounts for the chrome deposits frequently occurring in serpentine rock.

Iron (generally magnetic, often containing titanium) also

* R. A. F. Penrose *Pacific Coast Miner*, Vol. VII, p. 340.

forms ore-deposits in many basic rocks. As these rocks are, by their very definition, richer in iron than the silicious ones, iron deposits in general may be allowed to exhibit a certain preference for them.

Copper usually prefers basic rocks; on the other hand, there are many instances of rich copper deposits in silicious rocks.

Example: In Cuba, serpentine is abundant among the most ancient rocks. The serpentine is of igneous origin, being derived from the alteration of dark, basic, igneous rocks (such as peridotite). This rock is and has been considered the most productive of metals among the formations of the island. It contains large deposits of copper, ores of iron and chromium, and gold.*

Platinum was formerly only found in placers. In Russia, however, some years ago, the metal was found as an original constituent in peridotitic rocks, and late inquiry in America has fixed it as being in a number of such rocks. Prof. Kemp has reported platinum in peridotite from the Tulameen region, British Columbia. It was also reported from "fine-grained dark basaltic rock" in British Columbia in 1895 by Mr. Carmichael,† assayer for British Columbia. It seems, therefore, to be chiefly confined to the basic rocks, and it is, indeed, an intimate associate of chromite. Yet it has been found to occur, though less abundantly, even in so silicious a rock as syenite.

* Fernandes de Castro, Hayes, Vaughan, and Spencer. 'Geological Reconnaisance of Cuba,' 1901.

† *Engineering and Mining Journal*, Feb. 12, 1902, p. 249.

Most of the other minerals have, as far as known, slight or no preference for certain igneous rocks.

Preferences of Certain Igneous Rocks for Certain Ores, Displayed by Selective Precipitation of Metals from Solution.

May ores show a preference for one igneous rock over another, on account of the different effect of different rocks in precipitating ores from solution?

When ore-bearing solutions traverse a variety of igneous rocks, there will be certain chemical reactions between the so utions and the walls of the fracture which has afforded them a channel. Where the rock is porous and permeable, so that the solutions spread out and traverse it thoroughly and slowly, there the opportunity for such reactions is very great. In igneous rocks of different mineralogical and chemical composition, the same solutions will react in different ways, and the substances precipitated from solution as a result of these reactions will be apt to differ, both in quantity and quality. The result will be variable, and will depend as much on the specific character of the solutions (which vary greatly) as on the character of the rock.

Thus it may happen that an ore-bearing solution will form a rich deposit in one igneous rock and in another, along the same fracture, very little. Moreover, on account of the different character of solutions, a certain rock may in one case be selected by preference for ore-deposition, and in another case may be specially avoided.

Example: At Butte, Montana, two granites of different ages occur, one of which is ten per cent. more silicious than the other. The less silicious granite contains a considerable amount of hornblende and biotite, while the other contains very little. An important class of copper ores here have formed by replacement of the igneous rocks. The fractures, along which circulated the solutions that deposited the ore, cut both rocks. In the less silicious granite, the veins are commonly rich in copper; in the more silicious granite they are almost equally wide and strong, but are lean, and composed chiefly of quartz, with com-

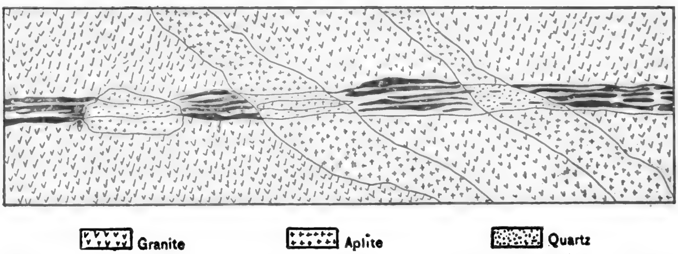

Fig. 8. Ideal plan of conditions in a copper vein at Butte, Montana, passing from less silicious granite into silicious granite. After W. H. Weed.

paratively little pyrite and copper. Microscopic study of the rocks show that in the process of replacement the hornblende was the first mineral to be altered to ore, indicating that the nature of the solutions were such as to react most readily with this mineral. It is believed that the presence of the hornblende and other dark minerals in the less silicious granite, and their absence in the more silicious rock, determined the preferential precipitation of the ores in the former.* (Fig. 8.)

* W. H. Weed, *Transactions* American Institute Mining Engineers, Vol. XXXI, p. 643.

ORE-BODIES IN THE RÔLE OF INTRUSIVE ROCKS.

Are metallic minerals ever thrust up in a molten condition in the form of dikes, requiring no further concentration to form ores?

It has been explained how certain metallic minerals may become segregated in molten masses so as to form ore-deposits. If these metallic segregations, instead of remaining where they originate, are disturbed by some movement, and forced up into the rock above while still wholly or partly fluid, it is conceivable that we should have dikes of ore. The occurrence of iron ore (magnetite) in this form has actually been reported.

Example: On Calamity brook, near lake Sanford, in the Adirondack Mountains, are dikes of titaniferous magnetite in anorthosite (a granular rock composed almost wholly of labradorite, a species of feldspar). The ore in the hand specimen appears to be an exceedingly ferriferous gabbro, and it contains inclusions of anorthosite, through which run little dikes of pyroxene, garnet, and ore that end in streaks of pyrites. The anorthosite inclusions are believed to be masses of the country rock which were torn off during the intrusion of the ore and about and through which gaseous action developed the little dikes, and streaks of pyrites. Thin sections of the ore-dikes, studied under the microscope, show coarsely crystalline aggregates of ilmenite or titaniferous magnetite, pyroxene, and a little biotite. Regarded as ores, they vary in richness, being sometimes nearly pure magnetite, and again more than half silicates.*

*J. F. Kemp, 19th Annual Report United States Geological Survey, Part III, p. 412.

IGNEOUS ROCKS INTRUSIVE SUBSEQUENT TO ORE-DEPOSITION.

May not intrusive igneous rocks sometimes form later than an ore-body, and so, though closely associated with it, yet have no part in its formation?

Just as faults may be earlier than ore-deposition in a certain case, and may furnish the channels along which the ore is concentrated, or may be later than ore-deposition, may cut and displace the ore-body, and, far from being a

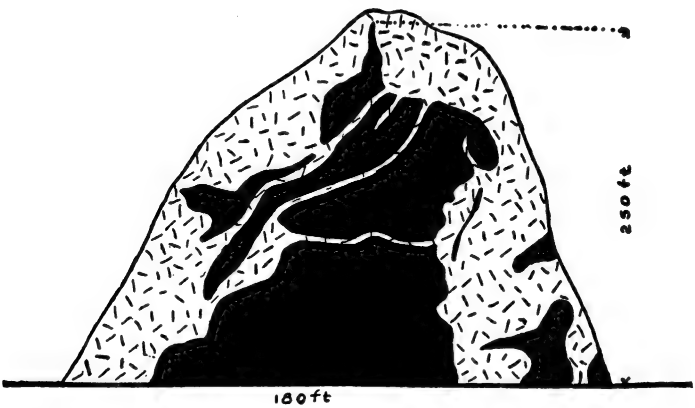

Fig. 9. Iron ore-bodies (hematite and magnetite), Lola mine, Santiago province, Cuba. Black portion is ore, surrounded by porphyry. After Hayes, Vaughan, and Spencer.

help in the ore-concentration, may be only a hindrance and vexation to the miner—just so an intrusive igneous rock may be earlier than ore-deposition and be largely responsible for it, or may be later and cut it up and separate it.

Where two igneous rocks are intruded at various times

in the same place, the ore-deposit resulting from the influence of the first intrusion may be broken by the second.

Example: The hematite and magnetite iron ores of Santiago province, Cuba,* have, since their formation, been cut, floated up, and surrounded by intrusive masses of porphyry, so as to entirely alter their form (Fig. 9).

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* Hayes, Vaughan, and Spencer. 'Geological Reconnaissance of Cuba,' 1091, p. 81.

CHAPTER IV.

THE STUDY OF DYNAMIC AND STRUCTURAL GEOLOGY AS APPLIED TO MINING.

PART I.

GENERAL CONCEPTIONS AND MAPPING.

DEFINITIONS.

What is dynamic geology and structural geology?

Dynamic geology is a study of the physical forces which produce changes in the earth's crust. These forces (due to the contraction of the earth from cooling, to migrations of molten rock beneath the solid crust, or to the unequal weight of different features of the surface, bringing about unstable equilibrium) produce bending and breaking in the rocks. Such disturbance is mainly noticeable in the stratified rocks, the beds of which are forced out of their original horizontal position into all manner of folds; or they are even broken, with one part thrust past the other along the line of fracture. This last is called a fault. The study of the arrangement or structure of these bent and broken rocks is called structural geology.

FOLDS AND FAULTS.

What is the meaning of the term dip?

The inclination of a bed (or other geological feature having a plane direction) is the *dip*, which is measured in degrees from the horizontal.

Should we use the word hade instead of dip, in speaking of veins?

The inclination of veins, dikes, faults, etc., is also called *hade*, and is measured in degrees from the vertical. There is, however, no need to have two opposing terms for any one thing, and it is better to apply the term dip to the inclination of the veins, faults, etc., as well as strata, and to measure it in the same way.

What are the principal kinds of folds?

Folds are chiefly divided into two kinds, according to whether they are open above or below. These are called respectively *synclines* and *anticlines*.

A line drawn from the *apex* of a fold (the highest point of an anticline or the lowest point of a syncline), midway between the two sides or *limbs* of a fold lies in the axis (Fig. 10).

If the axis is vertical, the two sides (or limbs) have the same dip; if the axis is inclined the dips of the limbs will be unequal, unless they are parallel, as when the folding is intense and they have been jammed together, forming a compressed or close fold. (Fig. 11).

The opposite of a close fold is an open fold (Fig. 10).

What are overthrown folds?

In open folds the limbs normally dip in opposite directions; yet the folds may be such that the limbs incline in

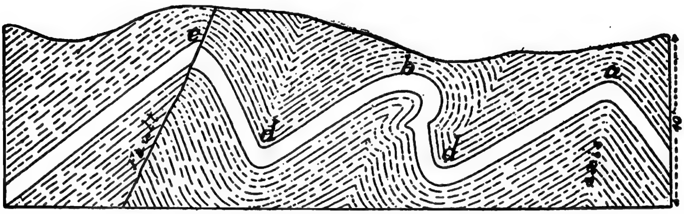

Fig. 10. Folding of limestones and shales on Kuskokwim river, Alaska. After J. E. Spurr,* a.=anticline; b.=anticline overthrown at the apex; c.=faulted anticline; dd.=synclines.

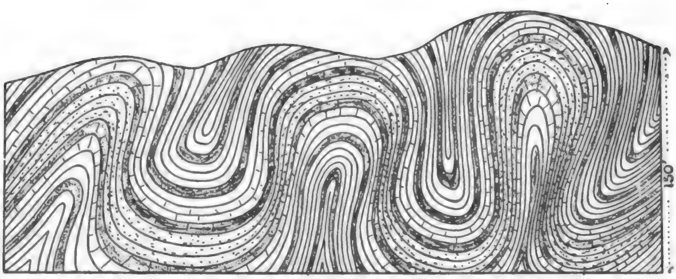

Fig. 11. Close folding in limy shales on Yukon river, Alaska, below Mission creek. After J. E. Spurr.†

the same direction, though not necessarily at the same angle. This constitutes an *overthrown* fold (Fig. 12). In extreme cases the axis may assume a horizontal position.

* 20th Annual Report United States Geological Survey. Part VII, p. 127.
† 18th Annual Report United States Geological Survey, Part III, p. 177.

What is a monocline?

Where strata suddenly change from a horizontal to an inclined position and then become horizontal again, a fold with only one limb—a monocline—is formed (Fig. 13).

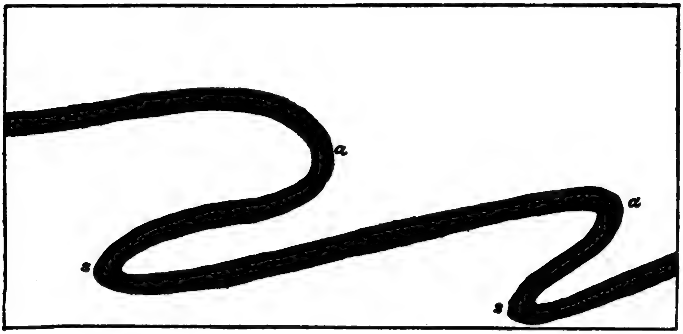

Fig. 12. Overthrown folds; aa. anticlines; ss. synclines.

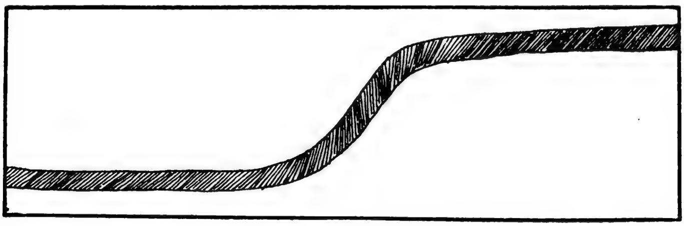

Fig. 13. Monoclinal fold.

What is a normal fault and what is a reversed fault?

Most fault planes have an inclination or dip between the horizontal and vertical. When the rocks on the upper side have moved down, relative to the rock on the under side, the fault is called *normal*. If the reverse movement has taken place, the fault is called a *reversed* or *thrust* fault.

The majority of faults are normal; but reversed faults are frequent (Figs. 14 and 15).

What are compensating faults?

Where a stratum or vein is faulted in many places it sometimes happens that one fault will displace the bed, and

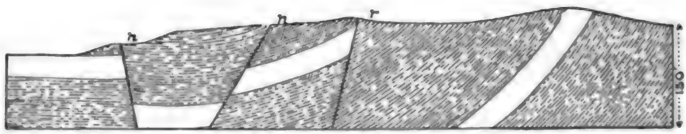

Fig. 14. Faults in strata, near Forty Mile, Yukon river, Alaska; nn.=normal faults; r.=reversed fault. After J. E. Spurr.*

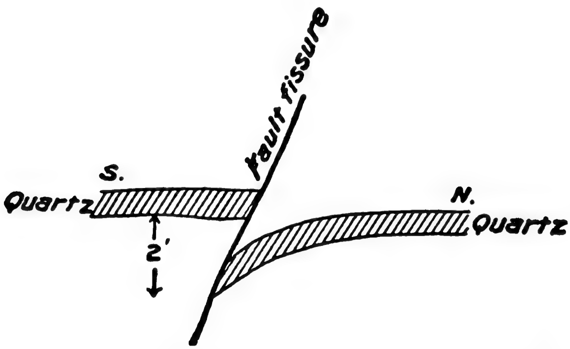

Fig. 15. Reversed fault, longitudinal section, Empire mine, Grass Valley, California. After W. Lindgren.†

another will bring it back to its original position. The two faults are thus compensating. In other words, the block comprised between the two faults has been moved out of line, leaving the rest in place.

* 18th Annual Report United States Geological Survey, Part III, p. 177.
† 17th Annual Report United States Geological Survey, Part II, p. 253.

Example: The accompanying figure represents compensating faults in the Omaha mine, Grass Valley, California. These faults displace a vein about one foot wide, consisting of quartz containing galena and iron pyrite, and other sulphides, with some free gold (Fig. 16).*

What connection have faults with folds?

A monocline may easily pass into a fault. Faults along

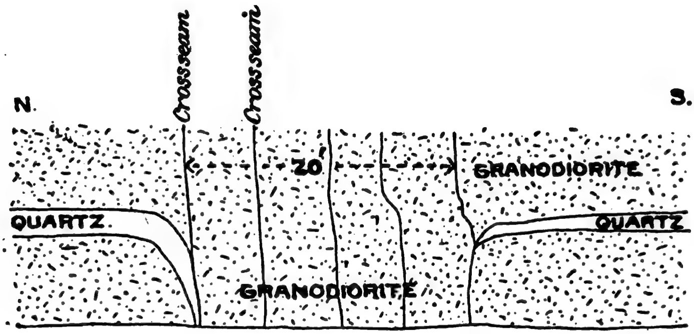

Fig. 16. Longitudinal section, showing fault, Omaha mine, Graha mine, Grass Valley, California. After W. Lindgren.

the axes of folds are also common, for along the axes rocks are weakened by bending and therefore liable to break. The directions of faults are likely to conincide with those of folds in the same region, for they both may originate as a result of the same kind of pressure.

* Waldemar Lindgren. 17th Annual Report United States Geological Survey, Part II, p. 243.

EFFECTS OF EROSION ON FOLDED AND FAULTED ROCKS.

What is erosion?

Erosion may be defined as the process of wearing away. As applied to geology, it signifies the wearing away of the rocks at the surface, chiefly by the action of streams.

Are folds and faults visible as such at the surface?

Deformation (as folding and faulting taken together may be called) would affect the earth's surface precisely as it does the rocks, were it not for the counteracting effects of erosion. Erosion is a slow process, but it is continuous. Folding and faulting is also a slow process—rarely spasmodic. It goes on beneath our feet today so gently that we do not notice it except where there is a slip in the gentle mechanism and an earthquake results. Sometimes deformation is more rapid in moulding the earth's surface than is erosion; sometimes erosion is the more active. But after deformation has stopped, owing to the easing of the deforming pressure, erosion still keeps on, so in the end it mostly has its own way and shapes the minor features of the earth to suit itself. Therefore, folds and faults are sometimes, but not usually, directly expressed as such at the surface.

What are the effects of erosion and deformation in producing topographic features?

Erosion and deformation are usually in opposition; the latter lifts up mountains while the former is engaged in

wearing them down. Both forces, even if each were left to itself, tend to produce irregularities—ridges and furrows—in the earth's surface. Simple deformation makes upfolds (anticlines) which are mountains, and downfolds (synclines) which are valleys. In the work of erosion rivers cut deep trenches which are valleys, and the high parts left between are the mountains. The first named are mountains

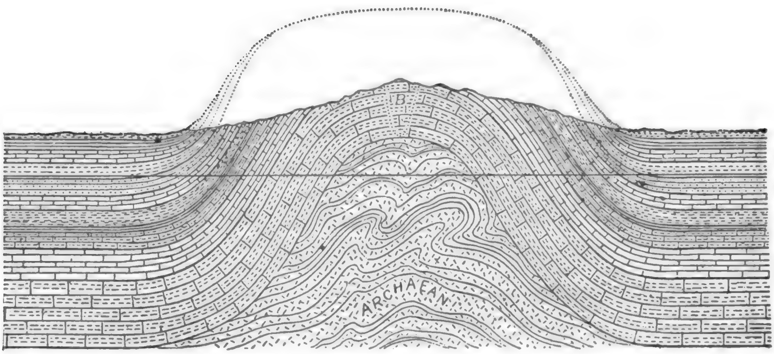

Fig. 17. Graded anticlinal range of deformation. A generalized transverse section of the Uinta range, Utah. After C. A. White.*

and valleys of deformation; the second, mountains and valleys of erosion.

Example: The Uinta range, in Utah, as shown in the accompanying figure (Fig. 17), is an anticlinal range, the upfold in the strata corresponding with the topographic dome. The great thickness of stratified rocks between the dotted line on the figure and the present mountain tops (a thickness greater than the height of the mountains above the plains) has been stripped off by erosion. Still, if the

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* 9th Annual Report United States Geological Survey, p. 694.

present relief of the range is directly due to the upfolding of the crust, as geologists have held, this is a range of deformation.

Are mountains of erosion upfolds of the crust?

Mountains of erosion are not necessarily upfolds. Upfolds tend to weaken the rocks so that they are more easily washed away, leaving valleys, with synclinal mountains between. Mountains may be composed of upfolds and downfolds together; and they may trend diagonally or at right angles to the trend of the folds.

In general, what relation has topography to folds?

As the result of these inharmonious processes, we may expect to find the relief or topography bearing any conceivable relation to the structure. In a hilly or mountainous region the structure is sometimes suggested by the topography, but more frequently the topography only obscures its elucidation. It even frequently happens that a highly folded region may have become by long erosion topographically a plain.

What is the relation between topography and faults?

As with folds, so with faults. Faults break the earth's surface and the moving of one rock past the other produces a cliff or scarp (simple fault-scarp). Only recent faults show this (Fig. 18).

The erosion which attacks a faulted surface may do one of several things, dependent on the different nature of the rocks on either side of the fault brought together by the

movement. There may result a scarp (erosion fault-scarp), a gully or valley along the fault, or the fault may not influence at all the outlines of the topography. An erosion fault-scarp is produced when the rock on one side

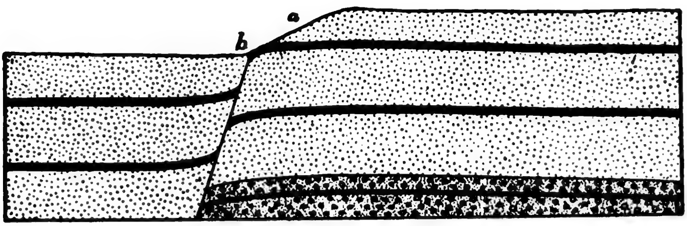

Fig. 18. Simple fault-scarp at the Palisades, Yukon river, Alaska; a.=fault-scarp; b.=fault. After J. E. Spurr.*

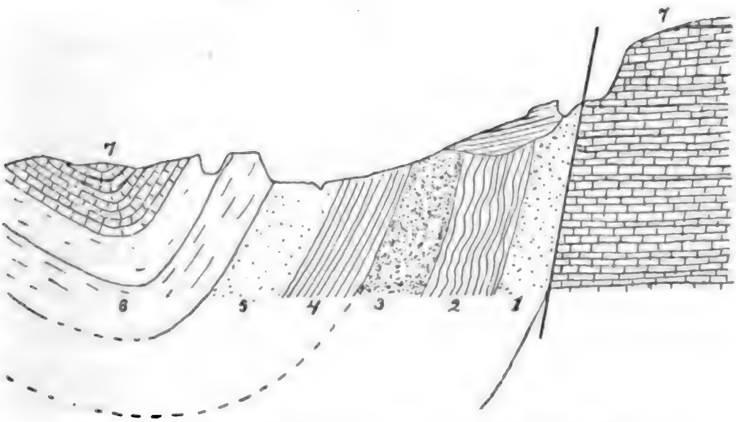

Fig. 19. Reversed erosion fault-scarp. Section in the Lower Austrian Alps. After Bittner.

of the fault is softer, and so more easily worn away, than on the other. If the rock on the upthrown side of the fault is harder than that on the downthrown side, the scarp will

* 18th Annual Report United States Geological Survey, Part III, p. 199.

face the downthrown side, that is, it will simulate a simple fault-scarp. This may be called a normal erosion fault-scarp. But if the rock on the downthrown side is harder, it will eventually become higher by the wearing away of the upthrown side, and the scarp will face this latter side. This is a reversed erosion fault-scarp (Fig. 19).

Since therefore we cannot tell beforehand what relation the rock structure will have to the topography, how are we to work out the structure problems?

Structure can be satisfactorily worked out only by reasoning from the attitude and position of the rocks as they appear at the surface or outcrop.

THE SURFACE MANTLE OF DÉBRIS.

Do rocks outcrop all over the surface?

When we start out to study the geology of a district, we find here one rock and there another; here a bed with a certain inclination, there another bed inclining with a different angle in another direction; then soil and forests without outcrops, valley bottoms free from hard rock, etc. The underground rocks do not outcrop continuously save in high mountainous regions.

Why do not rocks outcrop continuously?

Exposed rocks break up at the surface, under the influence of heat and cold, frost and thaw, rain and wind, the roots of trees and plants, and the decomposing acids, chiefly derived from vegetation, which soak down into the rocks and attack them. The result is that such rocks crumble

into sand and clay. Vegetation takes root, flourishes and dies, and new generations of plants arise; thus a top loam is formed, by the accumulation of vegetable remains. This loose decomposed material, or soil, is often found in place, directly over the solid rock whence it is derived. But, on account of its looseness, it usually moves downhill, into the valleys, and out towards the sea, in a steady but very leisurely journey. Thus steep mountain tops become stripped and expose only fresh rock, while their lower slopes are covered thickly with coarse fragments, and the valleys below are deeply filled with soil (wash or drift). Farther down the valleys, towards the sea, this wash is apt to cover larger and larger areas of solid rock (bed-rock) until at last it rests in the sea and there builds up a new series of sediments.

Besides the rocks that go to pieces slowly and thoroughly, a great deal is broken up more suddenly and violently by rapid mountain streams.

Are glaciers active in making soil and gravel?

Thousands of years ago, there existed a great *continental glacier*, (like that which now covers much of Greenland so deeply that we do not know where the land leaves off beneath it and the sea commences) over most of British North America east of the Rockies, and reached down into the United States. Its southern limit extended on the east into New Jersey, while on the extreme west it hardly got below the present northern boundary of the United States. In the mountains of some of our Western States such as Washington and Oregon, we still have local gla-

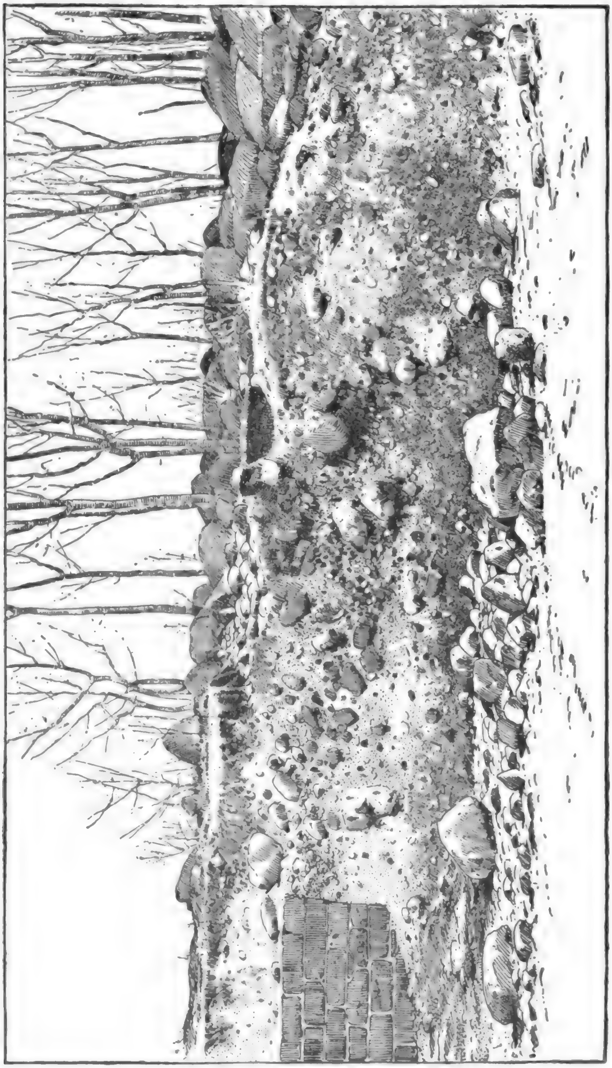

Fig. 20. Bank of Glacial Drift. Gloucester, Massachusetts. After N. S. Shaler. 9th Annual Report United States Geological Survey, p. 552.

ciers, occupying valleys, broad mountain sides or coastal slopes. Alaska contains many such glaciers, some of which cover thousands of square miles.

Glaciers are powerful rock crushers and erosive agents, and in their slow imperceptible forward flow they leave the material, which they have crushed and mingled, either beneath them or along their margins. Therefore the region of the old continental glaciers (the glaciated area) is generally thickly covered by broken and mixed rock and soil (glacial drift) from which the bed-rock peeps out only in places (Fig. 20).

Does this covering of soil and gravel make the unravelling of the structure difficult?

On the high mountains, where the rock is all exposed, it is possible for an observer of ordinary keenness to perceive the structure, unless it is complicated; but in a country where outcrops are not abundant it is difficult to read even simple structure.

THE SYSTEMATIC WORKING OUT OF GEOLOGIC STRUCTURE.

Strike and Dip.

How shall one start to work out the structure of folded and faulted rocks?

To work out the structure of a region, one must first learn to take the strike and dip of stratified rocks, for these rocks furnish the best key to the disturbances which the crust has undergone since their deposition. We know that they were

laid down horizontally: hence, when we find them tilted at a certain angle, we know that the crust at this point has been deformed to this extent.

How does one record strike and dip?

The dip has already been defined as the inclination of a bed, measured in degrees, from the horizontal. The strike is the direction of the outcropping edge of an inclined bed, on a horizontal surface (such as it would be on a flat plain)

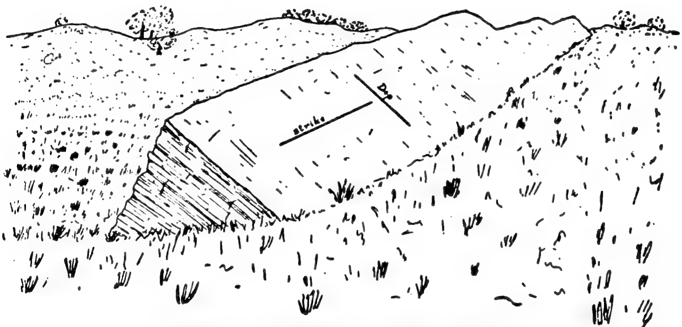

Fig. 21. The directions of strike and dip.

and is generally recorded in degrees from the north or from the south (Fig. 21). The writer prefers referring all readings so far as convenient, to the north point,—thus, N. 10° E., N. 90° E., N. 75° W., etc. The direction of the dip is invariably at right angles to the strike, but the inclination may be to one side or the other of the line of strike. Hence, in recording the dip, it is only necessary to note the general direction (the exact direction being known from the strike) and the angle of inclination. Thus, strike N. 60° E., dip 25° N. W.; or strike N. 35° W., dip 6° S. W.

How accurately should strike and dip be read?

It is generally useless to read the strike and dip closer than a degree; for the attitude of a bed generally varies constantly, though often slightly, so that greater accuracy in one place will not help in the broader problems.

How should the strike be read?

For this work a hand-compass, having a clinometer (arrangement for reading the dip), is sufficient. To read the strike, get the line of sight of the compass (the line between the sights, or the straight edge of a square compass) parallel to a line made by a horizontal plane cutting the surface of a bed, and read the angle between this and the north point of the compass needle. Thus, if this line is 30° to the right of the north point of the needle, (the observer facing in a northerly direction), its direction is N. 30° E. magnetic.

The reading may be corrected subsequently so as to read to the true north, by applying the known magnetic variation. The angle of this variation is to be added to the angle read, or subtracted from it, according to whether the variation in the region under examination is to the east or to the west of the true north. For example, in Maine at a place where the variation (declination) is 18° W. (that is, where the magnetic needle points 18° W. of true north) a magnetic strike reading N. 30° E. would be corrected by *subtracting* the variation, to N. 12° E. true; in Oregon, at a place where the variation is 20° E., the same magnetic reading (N. 30° E. would be corrected, by *adding* the variation, to N. 50° E. true.

How should the dip be read?

To read the dip there is, in the clinometer compass, a little weight which hangs down and so is vertical. One side of the square compass being held parallel to the dip of the rock, the number of degrees of this dip from the horizontal (or from the vertical, if one pleases) is registered on a scale across which the weight swings. There are other clinometer arrangements, but for ordinary geological work this simple one is as good as any. A graduated scale of degrees pasted on the cover of a notebook, with a small coin at the end of a thread, as weight, will also answer the purpose, the straight edge of the book being held parallel with the dip in measuring.

How can one best find the horizontal line?

In measuring strike and dip, it is best to judge with the eye the general horizontal direction and greatest inclination of an outcrop, and to hold the compass in the hand, away from the outcrop, as near these average directions as possible. The strike and dip usually vary much locally. Sometimes it is easiest to scratch a horizontal line on the exposed face of a bed, to get the true strike. One may remember that the dip is always the greatest inclination of a bed.

Recording Observations on Maps.

What is necessary for the continuance of the work?

The next necessary thing is to have some sort of map. If there is none on the proper scale, a small-scaled map may be enlarged, and corrected as one works. Where there

is none at all, a sketch map will have to serve. For such a sketch map, directions are easily found with a compass. Distances are got by pacing, with or without a pedometer; by an odometer attached to a carriage, or a cyclometer on a bicycle. Elevations can be taken with an aneroid barometer.

For accurate work, an accurate map is necessary. Such a map is most easily made with a plane-table, a method by which the surveying and the plotting go on simultaneously. The principal points are determined by triangulation, the elevations by means of vertical angles read with a transit, (or alidade of a plane-table) from the chief stations, and the minor points sketched and re-sketched from the different stations until they are approximately correct. For still more accurate work the position and elevation of nearly all the points are determined by stadia work. In these last two ways are made the beautiful contoured maps of the United States Geological Survey. Levelling may also be used for determining elevations. A contoured map, or at least one where the chief elevations are definitely recorded, is essential to any but the rudest of geological work, for it enables the student afterward to read and reconstruct the topography, without which the geology as exhibited on a plane map,—a projection of the real surface on a horizontal plane—can hardly be understood.

What does the student record on this map?

Upon this base-map the student should record every outcrop which he judges necessary. In a complicated country or where outcrops are few, often every rock

exposed is necessary. But where there are many outcrops of the same strike and dip and of the same kind of rock, or where the structure is simple, many may be omitted.

The outcrops which are recorded may generally be located on the map (especially a detailed map) by locating the topography of the place in question—*i. e.*, if the outcrop occurs on top of a hill, and the top of that hill is shown on the map, one can place the outcrop as closely as necessary. Where there are few landmarks, it is often necessary to locate outcrops instrumentally, by means of intersection from two known points, or by a direction and measured distance from some one known point, the result being plotted on the map according to the scale used.

How are strike and dip recorded?

For recording the strike and dip, the following sign is commonly used, the long line being the strike, and the arrow, with the angle written close to it, recording the direction and inclination of the dip (Fig. 22).

Fig. 22.

How should the different rocks be plotted?

The kind of rock may be written on the map, but it is better to use an arbitrary sign for each rock, or, better still, a color. A box of colored pencils may be used for this, and each color may be taken to represent one of the important rocks of the district in question. For example, blue can be used for limestone, brown for quartzite, red for granite, and so on.

When all the data are thus plotted, does it help our comprehension of the structure?

When all available outcrops have been recorded, the general distribution of each color, representing its particular formation, will be shown. In this way it often can be predicted, frequently with great accuracy, what rocks underlie the coverings of soil and glacial drift or valley wash, where there are no outcrops. By extending the line of strike in different outcrops of the same formation till they come together, the extension of beds under covering materials can be made out with especial certainty. If there is great and uniform disconnection along a certain line, between the strikes of such outcrops thus extended, then the geologist knows that this line is a fault-line, though it may not be visible to the eye (on account of covering material); and even the amount of discordance, or displacement of the fault, can often be closely calculated.

Migration of Outcrops.

Do the lines of outcrop of veins, faults, etc., on the surface, always give an accurate idea of their direction?

One must cultivate some geometrical perception to grasp the true attitude of beds, dikes, faults, etc., from the puzzling lines of outcrops afforded by the ordinary topographic surface, especially where this is irregular. The surface is a very uneven plane, which cuts these beds, dikes and faults at all angles, and since they themselves lie at all angles, the intersections may be infinitely varied. A bed or fault having a straight strike may have an outcrop

which will describe many kinds of curves when represented on the geologic map. The problem is: Given a plane cutting an uneven surface, where will be the intersection?—the plane being the bed, dike or fault, and the uneven surface the surface of the ground. Since the latter is always changing, the problem does also.

What is the explanation of this outcrop migration?

On a perfectly plane portion of the earth's surface, another plane, such as a sedimentary bed, dike, vein or fault, will outcrop as a staight line, whatever its dip. The only plane land surface which we find in nature continuing for a long distance is a horizontal plain. Here then a bed will outcrop in a straight line, following the direction of the strike. As soon as irregularities come in, the outcrop abandons the straight line and wanders in irregular curves and angles. This is so because *the further up an inclined bed is cut the further the outcrop moves horizontally in a direction opposite from the dip; the further down it is cut the more the outcrop advances in the direction of the dip.* The amount of the outcrop migration depends on the dip of the bed. In a vertical bed it is zero; in a horizontal bed infinity. It is necessary to be familiar with these laws, for often when an outcrop occurs it is important to know, both in geologic mapping and in practical exploring and mining operations, what is its course over a topographically irregular country, where slide-rock (talus), gravel wash, glacial drift, or vegetation renders continuous actual observation impossible.

How can one estimate the amount of outcrop migration where continuous observation is impossible?

By trigonometry, it is easy to find how much the outcrop of a bed of given dip will advance with the dip out of he line of strike, or retreat away from the dip out of it, with a given heightening and lowering. The change in height may be taken as the peipendicular side of a right triangle, and the dip as the angle opposite the perpendicular. Then the base is the horizontal migration of an outcrop (or the actual migration as projected on to a horizontal map), and the hypothenuse is the actual migration, as measured roughly on the surface, in an airline between the two extensions of two outcrops, and at right angles to the strike. The first measurement (the horizontal migration), is exclusively used in mapping; but a cross-section constructed from the map shows the actual migration graphically. In practical work an estimation of both the horizontal and actual migration will be often of value.

The formulas are as follows:

Horizontal migration = change in height multipled by the cotangent of the dip.

Actual migration = change in height divided by the sine of the dip.

Taking the change in height as 1:

Horizontal migration = cotangent of dip.

Actual migration = the reciprocal of the sine of the dip.

Following is a table for the most important dips:

The figures are calculated for a change in height of 1 unit. The concrete example of 100 feet has been taken.

Dip of bed, dike, vein, etc.	Change of height in topographic surface	Horizontal migration of outcrop.	Actual migration of outcrop.
0°	100 ft.	infinity	infinity
5°	100 ft.	1143 ft.	1147 ft.
10°	100 ft.	567 ft.	576 ft.
15°	100 ft.	373 ft.	386 ft.
20°	100 ft.	275 ft.	292 ft.
25°	100 ft.	215 ft.	237 ft.
30°	100 ft.	173 ft.	200 ft.
35°	100 ft.	143 ft.	174 ft.
40°	100 ft.	119 ft.	155 ft.
45°	100 ft.	100 ft.	141 ft.
50°	100 ft.	84 ft.	130 ft.
55°	100 ft.	70 ft.	122 ft.
60°	100 ft.	58 ft.	115 ft.
65°	100 ft.	47 ft.	110 ft.
70°	100 ft.	36 ft.	106 ft.
75°	100 ft.	27 ft.	103 ft.
80°	100 ft.	18 ft.	101 ft.
85°	100 ft.	9 ft	100 ft.
90°	100 ft.	0 ft.	100 ft.

Construction of Geologic Sections.

After plotting observations on maps, what is the next step?

The next step toward the comprehension of the structure is the construction of vertical sections. Cross-sections (at right angles to the line of strike) are the most serviceable.

Where should the cross-sections be placed?

These should be placed, first, where the surface outcrops give the most thorough data, and, second, neither in the most simple nor in the most complicated places (for the first sections, at least).

How is the base for cross-sections constructed?

The base for such sections is taken from the topographic maps. From a straight line, corresponding in length to the length of the line taken on the map, perpendiculars are drawn at the points where there are on the map data as to relative elevation. These relative elevations are then measured off on the perpendiculars, from the base line. The elevation of the base line may be stated as related to sea-level, where this is known, or to some other datum plane; or the line may be given an assumed elevation.

Should the vertical scale be different from the horizontal?

Frequently the scale used for plotting these elevations is greater (twice, three times, ten times as great) than that of the base line—*i.e.*, the vertical scale is greater than the horizontal. This gives, in the sections, exaggerated topography and exaggerated dips to the strata represented. But in most cases it is better to have the vertical scale the same as the horizontal, especially in large scale work and in mining work; this gives a more accurate, even if less accentuated, representation of the structure.

How is the outline of the topography obtained?

By drawing a line connecting the points thus marked out

on the verticals, a section of the topography results (Fig. 23).

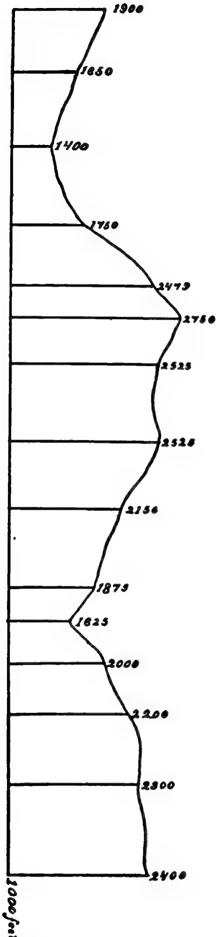

Fig. 23. Method of construction of a topographic base for geologic cross-sections. Scale 1 inch=1000 feet.

How are the geologic data put on this topographic section?

On this section the geological data found on this same line, on the geologic map, are plotted, the stratified rocks showing their dip. In places where there are no data on this line, outcrops not too far away may be represented by prolonging their line of strike till they intersect the section line. As in the map, different rocks may be represented by different colors.

The inspection, on this section, of the dips of a bed which outcrops at various places generally allows a correct reading of the structure, and an easy deduction of the attitude and location of the bed beneath other rocks, away from its outcrops. Thus the outcrops may be connected and the complete structure represented. Mines, wells, bore holes, etc., are all of the highest value for supplementing and fixing the elucidation of structure.

Cross-sections should be made at intervals, at a convenient distance apart. Often one well-established cross-section helps in the working out of the neighboring ones.

Are longitudinal sections ever advisable?

Longitudinal sections, parallel with the strike of the stratified rocks and at right angles to the cross-section, are sometimes valuable. Like the cross-sections, they are taken vertically and are constructed in the same manner. Cross-sections and longitudinal sections cross each other, and at the lines of intersection should be identical, so, when made independently, they are a valuable check on one another. When the data for one section are incomplete, an intersecting section may often supply it with data which will enable its being worked out. Both cross and longitudinal sections, when worked out, help to correct the surface geological map, and to establish more accurately the boundaries of the different formations, where these are concealed.

Economic Results of Mapping and Cross-Sectioning.

What is the economic application of this mapping and cross-sectioning?

In this way it can be ascertained what is the course of an economically valuable bed, such as one of coal, iron, salt, borax, oil or water, bedded veins of various metallic minerals, etc. The approximate position of such beds can be established beneath coverings of drift, and the proper places for sinking shafts to find these outcrops can be

determined. The sinking of shafts or the driving of tunnels in barren rock, lying next to the bed sought after, can be planned, and the distance that these drivings must be pushed to reach the bed may be determined beforehand. The same system, more carefully carried out, enables the tracing of an ordinary lode or vein outcrop under drift coverings; it makes the searching for the underground continuation of the surface outcrop of a vein, by means of new shafts and tunnels, in many cases, a matter of close calculation instead of guesswork.

What amount of geologic knowledge is necessary in order to be able to make such valuab'e studies?

To make such geologic studies it is necessary to be ab'e to recognize the different formations in the field—to distinguish sandstone, shale, conglomerate, limestone and quartzite from one another, and to have as much of an idea of igneous rocks as is given in the preceding chapter. Close determination of the rocks is usually not necessary, except for detailed work. The recognition of *the relation of the ores to a certain rock in the district in question, be that rock what it may, and enough science to follow that important rock both at the surface and under it, is the essential thing.* It does not concern the miner, in many cases, what the age of the rock is. One may observe that in a certain silver-lead district the ore-bodies are generally in or near a certain shale-bed—the problem is to follow that bed everywhere. In another district, one may remark that the ores occur chiefly near faults; then the problem is to search for the

faults of the district, to study which have been the most favored by ore-deposition, and to inquire into their horizontal and vertical extent.

Mapping and Sectioning of Igneous Rocks.

Can one reason out the underground continuation and position of igneous rocks in the same way as sedimentary rocks?

One must remember, in reasoning out structure, that sedimentary rocks conform to one another—that is, their bedding planes are parallel, for they were laid down one on top of the other, on the sea-bottom. But igneous rocks are not necessarily parallel to one another; neither do their boundaries, unlike those of the sedimentary rocks, have any constant direction. Thus it is difficult to reason out accurately the outlines of an igneous body beneath the surface; though the general ideas sketched in the last chapter will usually enable an approximation. One can decide whether the rock is a surface flow, the outcrop of a dike or sill or irregular mass, or is a fundamental body, and so can draw his conclusions as to the underground extension. Generally the direction and dip of dikes can be obtained from their outcrops; and a study of the fault, fold and joint systems in the rock frequently throws some light on the dike system also, for all are apt to be related.

PART II.

ROCK DEFORMATION AND DISLOCATION, AND THEIR CONNECTION WITH MINERAL VEINS.

MEASUREMENT OF FOLDS AND FAULTS.

Do rock folds have only two dimensions?

Folds and faults must be thought of, not only as they are represented on cross-sections, in two dimensions, but in all their three dimensions. Think of a sheet of paper folded and crumpled—the folds will not always be regular along the strike, but there will be uneven ridges and hollows. In geology a ridge, from which the rocks dip away on all sides, so that every section is anticlinal, is called a *dome;* a hollow, of which every section is synclinal, is a *basin.* It is possible, however, that an irregular fold may be anticlinal in one section; and in another, at right angles to the first, synclinal.

When can the displacement of a fault be estimated?

Where there is a number of different rocks, such as distinct beds, which the fault separates, it is only necessary to match the beds on one side of the fault with the same beds on the other side, to know approximately how much they have been separated. The contacts of igneous rocks,

or dikes, or faulted veins or ore-bodies, or even faulted faults (the fault having cut through and displaced a pre-existing older fault, as sometimes happens), may also be matched on the two sides of a fracture to measure its movement.

Is the separation of the parts of a faulted sedimentary bed always an accurate measurement of the amount of displacement?

A fault may lie in any plane (for example, it may be parallel to a sedimentary bed or perpendicular to it), and on this plane the direction of movement may be represented by any conceivable line. It may even be parallel to the plane of the sedimentary beds cut by the fault, in which case the beds will not be separated, no matter how great the movement; but a dike cutting these beds at right angles will be displaced by the whole movement of the fault (Fig. 28). *It is only when the plane of the sedimentary beds is perpendicular to the direction of faulting that the separation of the parts of a given bed is an accurate measurement of the movement.*

Do vertical cross-sections show accurately the displacement of a fault?

One is apt to consider faults simply as dislocations of sedimentary beds, and to assume that the amount of movement which appears on vertical sections is the whole displacement. The amount of displacement thus shown is easily found graphically, and is valuable as showing the

existence of a fault, and the break it makes in the sedimentary beds; but it does not necessarily convey an accurate idea of the whole displacement.

Is a more accurate measure of fault-displacement necessary to mining work?

Suppose that a spherical or lenticular or irregular ore-body is cut in the middle by a fault, and one half of the ore having been worked out up to the fault plane, it is the question to find where the other half has gone. In this case the separation of the strata (if the ore is in sedimentary rocks) as seen in a vertical section, gives absolutely no clue as to either the direction or the amount of displacement. In mining work, therefore, we must study more closely.

Can we measure fault-displacement in homogeneous rock-masses?

In homogeneous rock-masses the amount of movement in faults cannot be ascertained or even approximately estimated. The existence of a movement can be determined by the record left on the slipping surface or surfaces, in the shape of ground up rock, (fault-breccia), of polished and scratched (striated) rock surfaces (slickensides) etc. But the amount of friction shown by grinding and rubbing is not necessarily proportionate to the amount of movement, for some faults with slight displacement have thick crushed zones, while others of far greater movement show the effects of friction to a slight degree only.

Can we accurately measure fault-displacement in a heterogeneous rock mass?

In a rock mass composed of different kinds of rocks, we may measure with a greater or less degree of accuracy the amount of movement.

What are the chief aids in the work of measuring faults?

In mining geology it has been found that the more valuable aids are (besides sedimentary beds): igneous bodies, such as dikes; veins; bodies of ore; pre-existing faults; scratches (striæ) on the fault plane, showing the direction of movement; and the composition of the fault-breccia, which may show, in some degree, the direction and the amount of movement.

How do these things afford the necessary data?

The first four guides to displacement above mentioned are applicable because any continuous geologic feature, when broken and displaced, may be matched in imagination by the observer.

As regards the striæ, one rock moving past another along a fracture will mark the other rock with grooves parallel to the direction of movement. A given fault may have a strike N. 45° E. and a dip of 30° to the north-west. On this fault plane we may find that the striæ are nearly horizontal. We then know that along this fracture the faulted portions moved horizontally past each other. But we do not yet know in which horizontal direction a given side moved. Did the rock on the southeast side of the fault move to the northeast or to the southwest? This can

sometimes be told from a careful inspection of the striæ. Scratches that are narrow and deep at one end and become broad and shallow at the other are usually caused by movements toward the shallow side on the part of the rock which did the scratching; and, conversely, indicate movement toward the sharp end for the side which bears the scratches.

Regarding fault-breccia, we may take as example a faulted ore-body which leaves in the breccia a "trail" of ore, indicating the direction of movement. Concerning the breccia as a test for the amount of movement, the following may be said: If we find fragments of a certain rock, such as a granite or a sandstone, in the fault-breccia at a point where the wall rocks are both of different nature from these fragments, then the movement must have been at least as great as the distance from these fragments to the nearest place where granite or sandstone forms one of the walls of the fault.

Can faults be directly measured from the data in question?

Sometimes the fault-movement may be directly measured from the aids above mentioned; but more often it must be calculated from at least two of them. The direct measurement is possible, when the two parts of a separated ore-body have been found on the two sides of a fault, or where the intersection of a given dike with a given stratum has, in the same way, been found on both sides, or where it is otherwise possible to identify any given point on the two sides. With zones of homogeneous rock, such as beds, dikes and veins, the identification of any point is difficult

—hence the unreliability of these bodies alone as registrars of the true movement.

What are the functions of a fault movement, and how can they be calculated?

The following functions of a fault movement are important:

Dislocation and *displacement* are general terms, applicable to any part or the whole of a fault movement. Each of the functions defined below, and to which specific names are given, may be called simply a dislocation or displacement.

Total displacement is the distance which two points, originally adjacent, are separated by the fault movement; the line connecting these two points lies in the faultplane in all straight faults. It is occasionally possible to determine the total displacement directly by such criteria as are mentioned above; but ordinarily it can only be calculated or approximately estimated from some of its more easily measured functions.

Example: The total displacement of a fault can best be represented by a diagram. Fig. 24 shows a block of the earth's crust, which is represented for the purpose of illustration as being transparent. In the figure a portion of a given sedimentary bed is represented, traversed by a mineral-bearing vein (or it may be a dike of igneous rock). This bed and included vein are cut by a given fault plane, and the movement on the fault plane is such that the vein, at its intersection with the bed, is separated in the direction and by the distance *a b*. This distance is the real (maxi-

mum) fault-movement, or total displacement. On the earth's surface *c* is the outcrop of the fault plane, *d* of the sedimentary bed, and *e* of the vein.

The *lateral separation* is the perpendicular or shortest distance between the two parts of any continuous zonal body (such as a sedimentary bed), which has been separated by a fault, the distance being measured along the fault

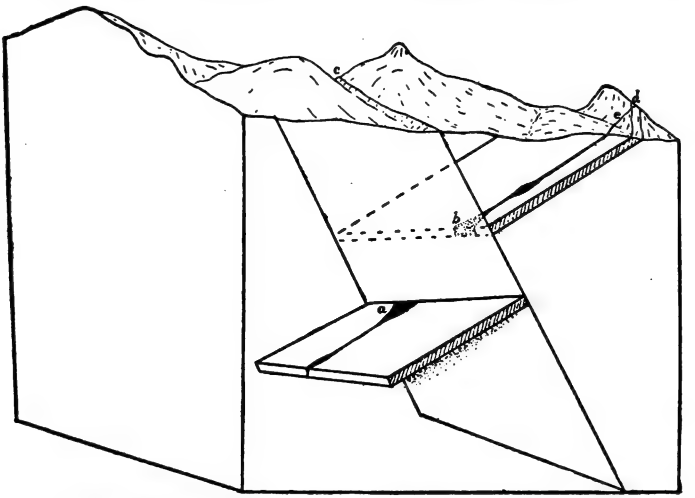

Fig. 24. Stereogram illustrating the total displacement of a fault.

plane. The lateral separation may be measured in a vertical, horizontal, or oblique line, according to the attitude of the bodies between which it is measured, and in any fault it may vary from zero to the total displacement. The total displacement may often be calculated from the lateral separation, since the latter is always the side of a right triangle of which the former is the hypotenuse.

Example: The lateral separation of a fault is shown in Fig. 25, where it is represented by the dotted line *bc*, while the total displacement is represented by the line *ab*.

The *perpendicular separation* is the perpendicular distance between the corresponding planes in the two parts of a single body available as criterion (such as a sedimentary bed), when this body has been separated by a fault, the planes on each side of the fault being projected for the purpose of measuring, if necessary.

Example: To illustrate the term perpendicular separation let us take Fig. 25. This is an ideal representation of a

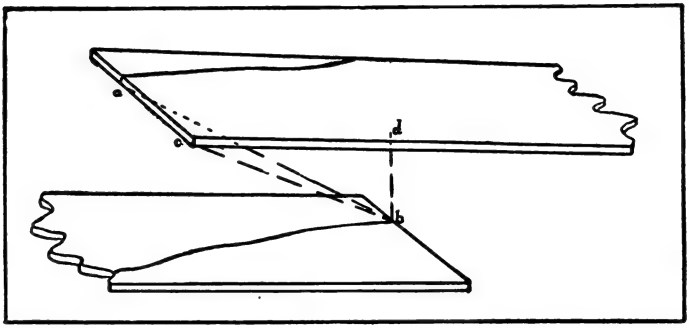

Fig. 25. Stereogram to illustrate various functions of a fault. *ab* is total displacement; *bc* is lateral separation; *db* is perpendicular separation.

portion of a sedimentary bed which has been faulted along the short straight edges of the pieces, so that the pieces come to occupy the relative position shown. Then the perpendicular distance between the two separated planes, represented by the dotted line *db*, is the perpendicular separation. If the fault was in the opposite direction, so that the broken pieces were separated by a gap instead of overlapping, then one of the planes would have to be projected in order to measure the perpendicular separation.

The perpendicular separation thus has a certain relation to the lateral separation; for it constitutes a side of a right triangle, the hypotenuse of which is the lateral separation, except in the possible case where the perpendicular and lateral separation coincide.

This mathematical relation makes it often possible to estimate the lateral separation from the perpendicular separation, and from the latter the total displacement.

Example: To illustrate the calculation of one of these measurements from another, let us look again at Fig. 25, where *ab*, the actual fault movement (being the distance by which the two portions of the intersection of the dike with the sedimentary bed are separated) is the total displacement, *bc* (drawn along the fault plane, perpendicular to the edge of the faulted bed, and hence the shortest line that can be drawn along the fault plane between the broken edges) the lateral separation, and *db*, the perpendicular distance between the planes of the separated portions, the perpendicular separation. Then *cdb* is a right triangle, as is *bca*.

Suppose a case that may often happen, that most of the figure represented is concealed, as shown by the shading in Fig. 26, only the light portion (which may represent an outcrop or a mining shaft or tunnel) being displayed. We may in any case measure the perpendicular separation. Then, taking the angle of the fault plane with the faulted stratum, we may calculate the lateral separation; for this angle deducted from 90° gives the angle *dbc* (Fig. 25). Then the perpendicular separation *db* divided by the cosine of *dbc* equals *bc*, the lateral separation. Suppose, again, the fault plane, as shown in Fig. 26, is scratched (striated) or shows lines of dragged material, indicating the direction

of movement. The accurate angle of this direction of scratching or dragging with a horizontal line drawn on the fault plane may be substracted from 90° to give the angle *abc* (Fig. 25). Then the already found lateral separation *bc*, divided by the cosine of *abc*, gives the total displacement *ab*.

Of these three functions, the perpendicular separation is most easy of measurement, and its value may vary from

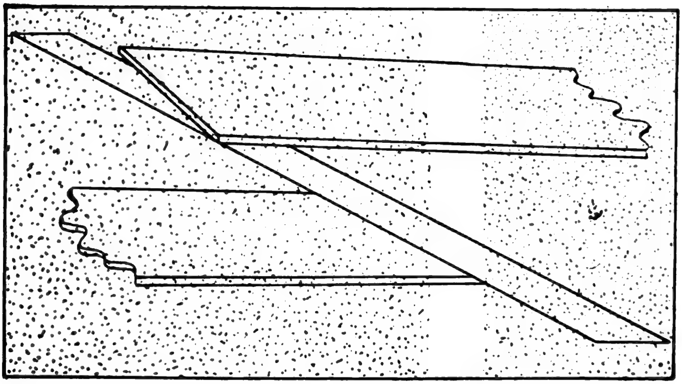

Fig. 26. Stereogram to illustrate the computation of a fault movement, where a part of the data is concealed.

zero to the full amount of lateral separation. The lateral separation is easier to ascertain than the total displacement, and its value may vary from zero to the total displacement. In Fig. 27 a case is illustrated where the lateral separation, the perpendicular separation, and the vertical separation* of the faulted beds are zero; but

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* See p. 160.

if an ore-body has been faulted as represented in the figure, then the throw and the offset,* which in this case coincide with each other and with the total displacement, may be measured.

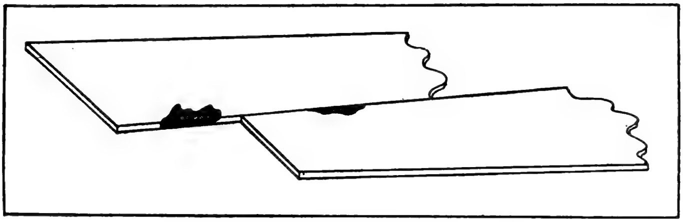

Fig. 27. Stereogram of a fault in which the lateral separation, the perpendicular separation and the vertical separation are zero.

Example: Fig. 28 is an ideal representation of that class of faults where the movement takes place along the bedding planes of stratified rocks—bedding faults. With regard to the functions of such a fault, it will be observed that, as far as the stratified rocks along whose bedding the fault occurs are concerned, the fault has no perpendicular separation nor vertical separation; and the other functions are usually impossible of measurement.

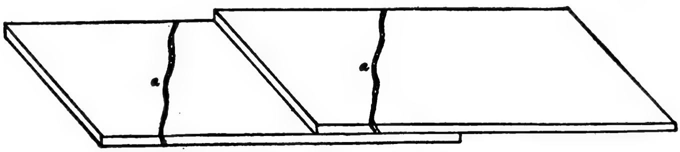

Fig. 28. Stereogram illustrating a bedding fault.

Where, however, as is represented in the figure, a dike or vein runs across the stratification and is displaced by the fault, this affords opportunity for measuring the throw or offset (which coincide in this case). Moreover, the perpen-

* See pp. 159, 162.

dicular and lateral separation of the dike may be measured, and perhaps the total displacement may be approximately calculated or directly measured, as for example, between the parts of the characteristic curve *a* (distance *a-a*).

The measurements which have been defined have no constant direction, since they refer to fault movements which are capable of infinite variation. In general geological work, however, it is often only possible to measure fault movements along certain arbitrary planes. The most valuable of these planes are, the earth's surface, which may be considered a horizontal plane, and vertical sections, into which available data are put, with the gaps in the chain of information often theoretically filled out. In such cases, where some dislocation is evident, but the formation is so meager that it is not possible to know the fault so accurately as to estimate even approximately its total displacement, or lateral or perpendicular separation, it is necessary to employ specific terms to designate the known or estimated dislocation, although the relations of these dislocations to the total displacement may be unknown. For this purpose the terms offset, throw and vertical separation may be used. The terms *throw* and *vertical separation* are applied to the dislocation of a fault as seen in a vertical section; the term *offset*, to the dislocation as seen in a horizontal section, such as the earth's surface may be considered to be.

The *throw* may be defined as the distance between the two parts of any body available as criterion (such as a sedimentary bed) when these parts have been separated

by a fault, the distance being measured along the fault plane, as shown in a vertical section.

The *vertical separation* is the perpendicular distance between the intersection of any two parts of any faulted body available as criterion (such as a sedimentary bed), with the plane of a vertical section, the lines of intersection being projected if necessary for the purpose of measurement. In perpendicular faults the vertical separation is identical with the throw; in all others it is less than the throw, but sustains a certain relationship to it, being one side of a right triangle of which the throw is the hypotenuse. Thus the vertical separation may vary from zero to the full amount of the throw. The throw is always a part of the total displacement, although with no definite relationship to it, and varies from zero to the total displacement.

Example: Fig. 29 is an ideal vertical section of faulted stratified rocks; *ab* is the vertical separation, *ac* the throw. Suppose the whole belt occupied by the fault covered from observation in some way: then the only evidence of faulting which we have would be the fact that in different places we find the same bed in different positions, and if we project the different known parts of this bed, they will not meet. This would be evidence of the probable existence of a fault, but we would not know the direction, nor angle of it, and so would be unable to measure the throw even approximately. We would, however, be able to measure the vertical separation. If the fault represented in the diagram were perpendicular to the strata, the vertical separation would coincide with the throw; if it were horizontal the vertical separation would be zero.

Fig. 30 represents the relations of throw and vertical separation, more diagrammatically, and in the case of a reversed fault.

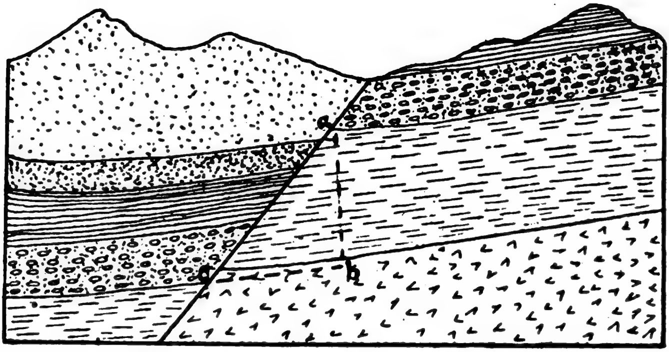

Fig. 29. Illustrating fault functions.

The vertical separation being measured, the throw may be calculated, if the attitude of the fault is known; for the

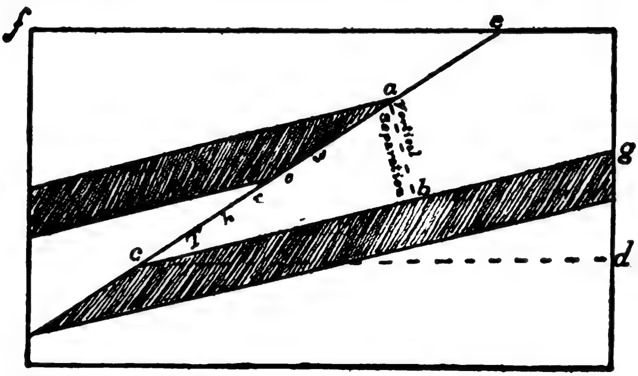

Fig. 30. The relations of throw and vertical separation, in the case of a reversed fault.

inclination of the fault (as shown in a vertical section) from the horizontal, minus the dip of the faulted beds,

equals the angle *acb* (Fig. 30.) (*fec*, the dip of the fault, equals *ecd*, which, minus *gcd*, the dip of the bed, equals *acb*.) Then the throw equals the vertical separation divided by the sine of *acb*.

The term *offset* may be used to designate the perpendicular distance between the intersections of corresponding planes in the two parts of any faulted body available as criterion, such as a sedimentary bed, with a horizontal plan such as the earth's surface may be considered to be; the planes being projected for the purpose of measuring, if necessary. Like the throw, the heave or offset is a part of the total displacement, but has no definite relationship to it.

Example: Fig. 31 shows a horizontal surface plan, comprising a lake and rivers. The outcrop of the dotted bed is displaced by the fault, and the offset of the fault is indicated by the dotted lines. If it is desired to find the distance, along the outcrop of the fault plane, of the two parts of the bed separated by the fault (a function which we may term the horizontal throw), this distance may be calculated from the offset and the direction of the fault outcrop, in the same manner as indicated for the vertical throw and the vertical separation.

To sum up, there are six terms which may designate the different parts of a fault movement, each term applying to a measurement which varies in accuracy and proximity to the total displacement in proportion to the available amount of information. For general outline work where ac-

curate data are not obtainable, the terms throw and vertical separation, referring to the measurement of a fault at its intersection with a vertical plane, and the term offset, indicating the measurement of a fault at its intersection with a horizontal plane, are adopted. The throw and offset are parts of the actual fault movement, but of unknown value, while the vertical displacement sustains a certain relation-

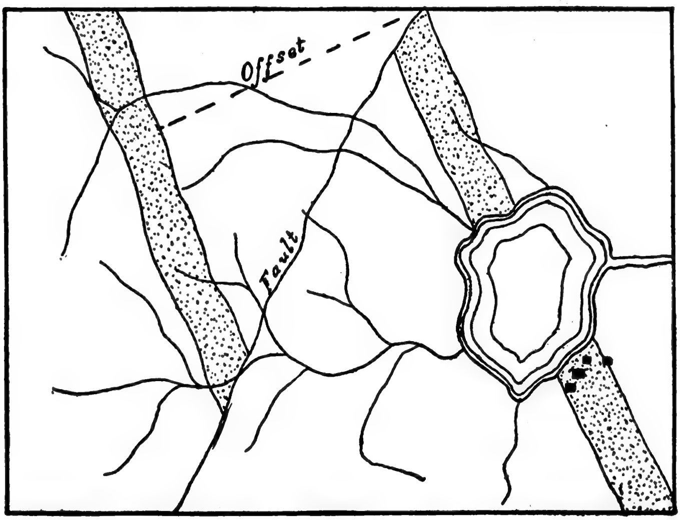

Fig. 81. Diagram illustrating the offset of a fault.

ship to the throw. Where more complete data are obtainable, the terms total displacement, lateral separation, and perpendicular separation are adopted. The perpendicular separation sustains a certain relationship to the lateral separation, as the lateral separation does to the total displacement.

FOLDS AND FAULTS AS LOCI OF ORE-DEPOSITION.

Deposition of Ore in Folds.

In what cases are ores formed by preference in synclines or anticlines?

Where there is a stratum impervious to water and that stratum is folded with others, downward moving waters

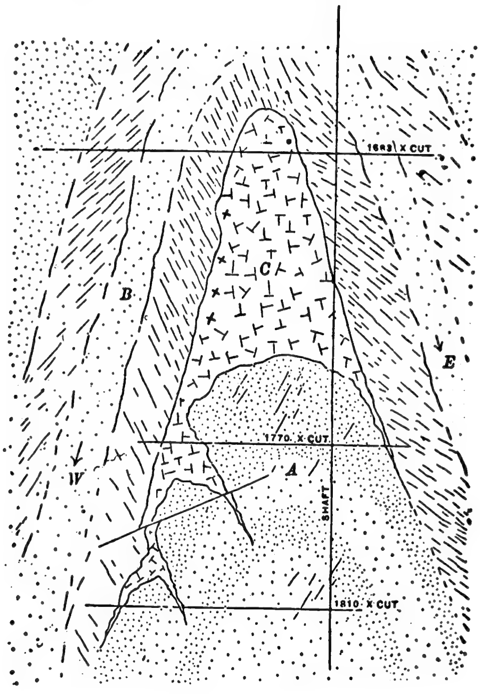

Fig. 32. Auriferous Saddle Veins. New Chum Consolidated Mine, Bendigo, Australia. ***C*** **is quartz in apex of saddle. After T. A. Rickard.**

will be arrested in the bottoms (troughs) of synclines (downfolds), and upward moving waters in the tops of

anticlines (upfolds). If the waters are mineralizing, the ores will be deposited by preference in these places. In a given district the chief mineralization has generally been brought about in large part either by upward or by downward moving waters, so that the ores may be found either in the anticlines or the synclines, as the case may be; and once the law has been discovered it is easy to follow. For example, if it is found that the tops of the anticlines are likely to carry ore, all anticlines must be prospected.

Example: In the Bendigo gold-fields, Australia, auriferous quartz veins occur in highly folded Silurian sandstones and slates.* The ore-bodies are apt to be especially large and profitable at the apex of anticlines, forming so-called "saddles" (Fig. 32), while in synclines similar deposits, called "inverted saddles," though recognized, are rare and unimportant.

Do folds need to be pronounced, in order thus to determine ore-deposition?

Undoubtedly a strong fold in a relatively impervious stratum is more favorable than a weak fold for producing the localization of ores deposited by circulating waters. Yet a slight flexure, such as a slight transverse trough or arch in already highly folded and steeply dipping beds, may determine ore-deposition and the location of an ore body.

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* T. A. Rickard, *Transactions* American Institute Mining Engineers, Vol. XX, pp. 463 *et seq.*

Example: The ores of the Elkhorn mine, Jefferson county, Montana,* lie on the under side of the contact of limestone (below) and hardened shale (above). These strata dip 35° to 50° uniformly in the same direction, forming part of the main fold of the region. In this fold there are several minor transverse corrugations, forming arches and troughs. The ores occur in two of the lesser arches, which pitch steeply with the general dip of the strata and unite near the surface to form a single broader arch. Along the contact of limestone and hardened shale the limestone has been crushed by slipping in the process of folding. This crushed rock formed the channel for uprising

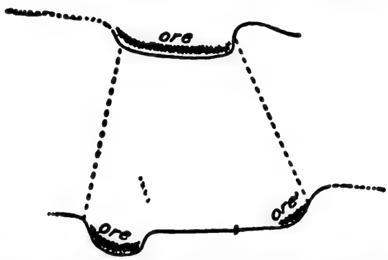

Fig. 33. Occurrence of ore shoots in pitching arches or folds of the strata, Elkhorn mine, Montana. After W. H. Weed.

metalliferous solutions, which were confined under the arches by the overlying relatively impervious hardened slate, and there the ore was deposited (Fig. 33).

Why do oil and gas often occur at the summits of anticlinal folds?

The same principle that arrests and accumulates ascending waters in the summits of anticlines holds good for other fluids. Of great interest in this respect are oil and gas,

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*** W. H. Weed, 22d Annual Report United States Geological Survey, Part II, pp. 492-495.**

both of which, forced upward under pressure, often accumulate under anticlines, especially anticlinal domes, even if the folds be very gentle and often barely perceptible. Borings for oil or gas are generally directed by preference to these anticlines.

Is this the only reason why the crests of anticlines are often selected as sites of ore-deposition?

In the process of folding the tops of the anticlines are the most pulled apart, the troughs of the synclines the most compressed; hence at the tops of the anticlines

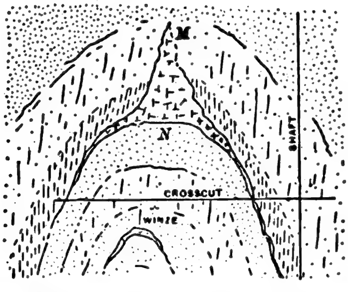

Fig. 84. Vein formation in the apex of an anticline. New Chum Railway mine, Bendigo, Australia. *M N* is apex of saddle occupied by quartz. After T. A. Rickard.

there is likely to be a strong jointing and fracturing. This permits the passage of waters and so determines a water-course; and if the waters contain metals they may be precipitated here.

Example: 1. In many of the saddles of auriferous quartz in the Bendigo gold-fields Australia, mentioned above, the vein penetrates upward through the beds along

the axis of the anticlinal fold. in such a way as to indicate that it has selected this position on account of the zone of weakness. Fig. 34, showing an ore-body in the New Chum Railway mine, is illustrative of a number of such cases described by Mr. Rickard.

2. The mining district of Tombstone, Arizona, has as rock formations a sedimentary series of limestones, quartzites and shales, intruded by granodiorite* and overlain by rhyolite. The sedimentary rocks are also cut by many small dikes of granitic and dioritic rocks. The series has been folded, producing anticlines, which are often highly compressed, and occasionally faulted; and to

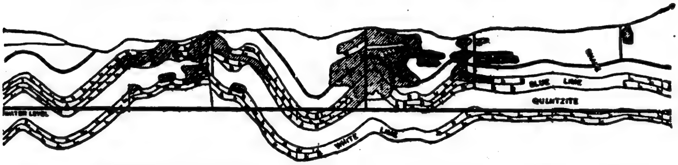

Fig. 35. Deposition of ores in anticlinal folds. Tombstone district, Arizona. After John A. Church.

this folding and fissuring the rocks owe their ore. These ores extend along the stratification, as bedded deposits, or cut across it as true veins, or again have quite an irregular shape; and all of these types run into one another. The bedded deposits and the veins lie in general in the anticlines, while the synclines are barren. Although the evidence suggests that the ores have been deposited from uprising waters, there is no impervious stratum which has arrested the upward passage of the solutions and brought about precipitation. In one anticline there may be as many as three separate sheets of ore, one over the other.†

*** A granular rock intermediate in composition between granite and diorite.**

† John A. Church, *Transactions* American Institute Mining Engineers, Vol. XXXIII, pp. 3-37.

The result of folding has been to produce openings in the anticlines, both between the strata and as cross-cutting fractures; these openings have constituted channels for rising waters, and along them the ores have been deposited where favorable opportunities, such as a chance for replacement of the limestones, offered themselves (Fig. 35).

Deposition of Ore Along Faults.

Why are ores often formed on or near faults?

Mineralization often takes place along fault zones because these have afforded the most available circulation channels for the mineralizing waters.

Example: An example is found in the Aspen district, Colorado.* Fig. 36 is a section in the Bushwhacker-Park Regent mine, showing this feature. The ores have chiefly formed along a fault which makes only a comparatively slight angle with the stratification, and especially at the intersection of this fault with others. Thus the ore-bodies are restricted to certain localities on the faults, while other parts of the faults are slightly or not at all mineralized. The reason for this is partly because some of the faults originated subsequent to the chief period of ore-deposition; but chiefly because the junction of two faults made very favorable conditions for ore-deposition, as explained in the paragraph on the principle of intersections (See p. 196).

Are the largest faults the most favorable for ore-deposition?

The magnitude of the fault has no relation to the relative likelihood of ore-deposits, for the favorable circumstance is

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* Monograph XXI, United States Geological Survey, pp. 229-231.

the fissuring and crushing, producing channels of circulation, and not the fault movement. Thus a very slight fault may be far more thoroughly mineralized than a large one.

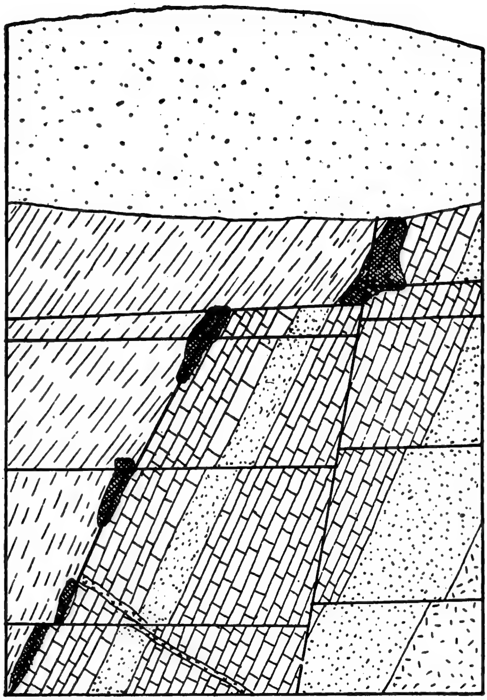

Fig. 36. Cross-section of Bushwhacker-Park Regent mine, Aspen, Colorado. Dark-shaded areas are ore-bodies. Heavy black lines are faults. After J. E. Spurr.

Why, in a faulted country, are the ore-bodies irregular and why do they often form rather near the faults than on them?

A fault is generally not a single plane; it is a zone of close-set fractures, the movement being most intense along

a certain line and dying out slowly on both sides. Frequently the rock on both sides of the fault-zone is thoroughly wrenched and seamed with tiny cracks, even where it appears solid to the naked eye. The mineral solutions are more effective among slight fractures than in a large fissure; thoroughly seamed rock is a very favorable place for ore, because the solutions are checked and held in a way that seems fitted for the working of the reactions which lead to the precipitation of ores. If mineralization is slight along the main fault fracture it may be considerable along some of the auxiliary fractures, and in the strained rock near by. This is especially the case in limestones, where great deposits thus originate. Therefore the search for mineralization along a fault plane, in districts where the two are associated, should extend over a comparatively wide zone.

Example: 1. The veins of Rico, Colorado, as described by T. A. Rickard and F. L. Ransome, are mostly along fissures which have been opened by faulting. The displacement of these faults, as shown on each side of the veins, is, however, generally less than 10 feet. As a rule, the more important faults of the region are not attended by much ore. The ore-bearing fault is often a slight auxiliary slip, occurring beside the main plane of movement of a larger fault, which is barren.

The result of dynamic strain in this region was the development of planes or zones of weakness, cracks and fissures; and along these there was generally movement of the rock on one side past the rock on the other. All of these openings became the channels of circulating mineral-bearing waters. In the smaller channels, however, (which naturally were along the smaller faults) the circulation

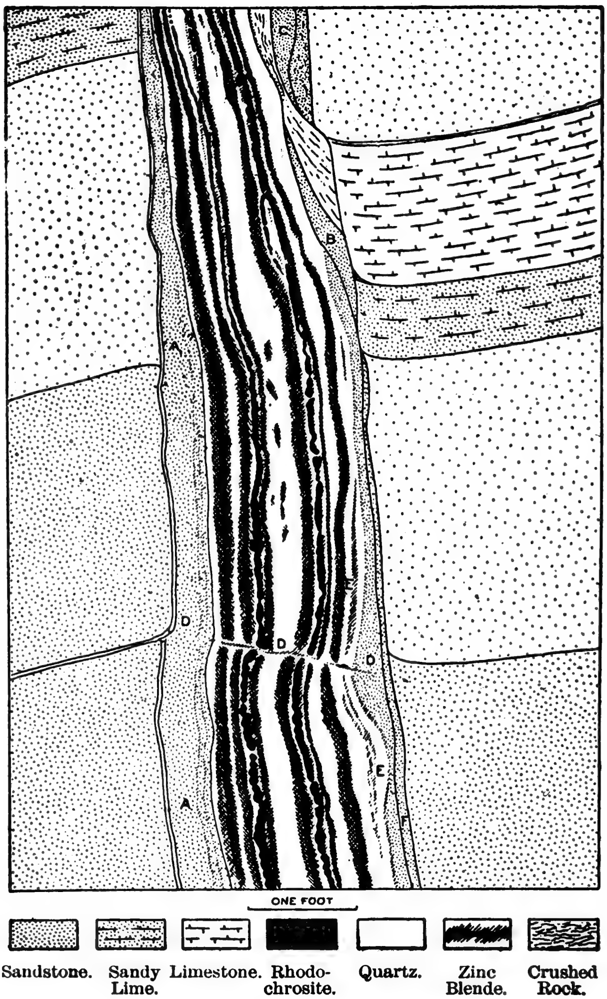

Fig. 37. Ore deposition in fissure along a minor fault. Section across the Eureka vein, Rico, Colorado. After T. A. Rickard.

was slow, so that plenty of time was given for the processes of deposition to act; while in the larger channels the circulation was probably in many cases so rapid as not to allow much precipitation along them. Fig. 37 shows a fissure vein along a minor fault.

2. In the Queen of the West mine, Ten-Mile district, Colorado, are sandstone and shale beds, with generally conformable porphyry sheets. Faulting has taken place along a series of parallel and closely contiguous planes, so that the rock has been divided into thin sheets, each of which has moved past the other a certain distance. In the central part of the fissured zone the spaces between the sheets have been filled with vein material, and the sheets themselves decomposed, impregnated, and somewhat replaced by it. The resulting condition is puzzling for the miner who expects to find his ore bounded by well-defined walls. There are here walls in abundance, but no one wall can be followed continuously for any great distance. Therefore it is the custom to run frequent cross-cuts away from the main drift (which follows the central zone) and these cuts disclose ore-bodies running parallel to this zone, now on one side and now on the other, and often 15 or 25 feet distant from it.*

JOINTS IN ROCKS.

What are joints in rocks?

Joints are planes of fracture, or divisional planes, which run through rocks. Few rocks are without them. Fragments of broken rocks are often more or less completely

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* S. F. Emmons, *Transactions* American Institute Mining Engineers, Vol. XVI, p. 837.

bounded by plane surfaces, whether the rock is igneous or stratified. In stratified rocks one or two of the plane surfaces are apt to be due to the stratification; the others are joints. In igneous rocks all the planes are usually joints.

How are joints produced?

Joints are produced by the application of force to the rock. Earth movements may cause a strain or twisting—the result is a system of cracks, such as we find when ice or glass is put under such strains. According to the nature of the stress, the number of joint systems vary, together with their general direction and their direction relative to one another, and the relative abundance of joint cracks in the rock.

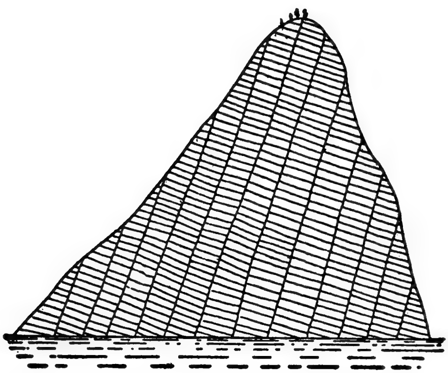

Fig. 88. Columnar jointing of basalt, Koyukuk mountain, on the Yukon river, Alaska. After J. E. Spurr.*

* 18th Annual Report United States Geological Survey, Part III.

Are all joints formed by regional strains?

Another kind of joint is formed by contraction. This is found in most lavas and in many small dikes. The heated rock shrinks and cracks on cooling. The resulting jointing is usually systematic; it runs in the direction of least resistance and hence is vertical to the planes of the flow in lavas, and perpendicular to the walls in dikes. Its effect is to divide the rock into columns—hence the term *columnar structure* (Fig. 38). This columnar jointing may also originate by reason of rocks shrinking through chemical changes.

ORE-DEPOSITION ALONG JOINTS.

What advantage is there to the mining man in the study of rock-joints?

Joint-planes have nearly uniform directions for long distances, traversing even folded beds. Since they are the record of strains in the earth's crust, their study should never be neglected by the student of mining geology. Frequently there is an observable connection between them and fold and fault systems, mountain ranges, etc., in the same district. Moreover, joint planes, especially when closely set together, furnish a channel for underground waters. Hence the joint systems may correspond to the vein systems in a given district, and a study of the former helps in exploring and exploiting to best advantage the latter.

Example: The mining camp of Monte Cristo, in the Cascade Range, Washington, is in a district where ninety-

nine per cent. of the ores have formed along joint-planes. These planes have furnished channels for circulating waters and as a consequence the minerals which these waters carried have been deposited near the joints (Fig. 39). A study of the laws of jointing here is directly applicable to the mineral veins, for every peculiarity of the jointing is copied by veins, with the added complication that the vein (following the former or even present channel of easiest circulation for waters) may pass from one joint to another.

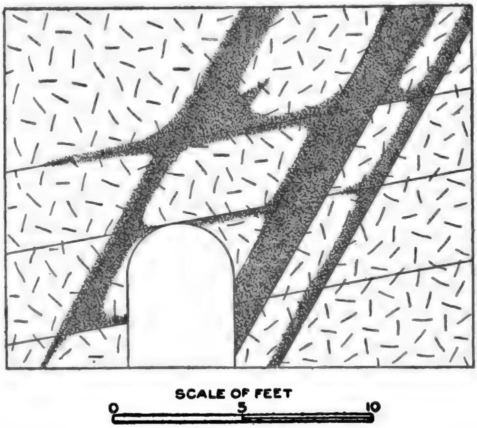

Fig. 39. Formation of ores along joints. Tunnel and vein exposures in vertical cliff, Glacier creek, Monte Cristo, Washington. After J. E. Spurr.

How should one study joints so as to arrive at an understanding of the system?

The strikes and dips of joints in various places should be recorded on the map by the same symbol given for stratified rocks; an accumulation of these records and their combination usually enables one to comprehend the joint-systems.

FRACTURES AND FISSURES.

What is meant by the term fractures as used in mining geology?

The term fractures is generally applied to cracks in rocks, large enough to be distinctly visible to the naked eye. The fractures may also come under the head of joints, in which case they are joint fractures or joint cracks; or, if there has been movement along them, they may also be faults and fault fractures. As generally used, the term denotes a break of an importance intermediate between a joint and a fault, as these latter are most commonly employed.

Fractures are, like joints and faults, the result of the straining and cracking of rocks under pressures. A fault plane is usually accompanied on both sides by parallel fractures extending a greater or less distance away from it, and there may or may not be faulting along them. In regions where the rocks have been jointed by stress, one or several of the systems may be so strongly developed as to cause marked fractures, often a conspicuous feature in the general appearance of the rocks.

In what way is this stress applied so as to form fractures and fissures?

According to the way motion takes place in the crust, certain portions may be stretched or compressed. By both these methods fractures and fissures may originate; in the former by the production of actual cracks from the stretching; in the latter by the greater action of the compressive strains along certain lines, there producing zones

of more considerable crushing, shearing and faulting. It is certain that open cracks and fissures may be formed directly from stretching (tension); while, from the nature of things, it is impossible that openings are directly produced by compression. In the case of fracture zones resulting from compression, however, release of the pressure may allow them to open somewhat; they then become the channels for circulating waters, and these may dissolve or otherwise carry away the broken or ground-up material, leaving a continuous opening or series of openings.

Twisting or torsion of a rigid body has been experimentally found to produce systems of cracks intersecting at

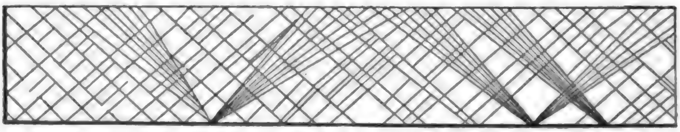

Fig. 40. Sheet of glass cracked by torsional strain. After Daubrée.

right angles. The force in this case seems to be tensional (Fig. 40). This process probably takes place in the earth's crust.

Earthquake shocks probably produce shattering and fracturing of the rocks. This also is a sort of tensional stress.

Eruptions and intrusions of volcanic material may cause fracturing and fissuring of the rigid rocks through which they pass, especially in the general neighborhood of the surface.

What are conjugated fractures, and how are they formed?

It has been shown experimentally and by calculation that compressive stress, applied horizontally in a given direction (for instance, from north to south), will produce two systems of fractures, striking east and west, and dipping respectively north and south at angles of about 45°. These two systems of fractures, parallel in strikes but opposite in dip, are designated conjugated fractures.

Are fractures straight, or irregular?

As a rule, fractures, like joints and faults, being due to stress, are straight, approaching as near as possible mathematical planes. In rocks which are uniform in texture and resistance, therefore, fractures generally deviate but little from a straight course; but as nearly all rocks are more or less irregular in these particulars, small and even large irregularities will be found in actual fractures. The same is true in fault planes.

Example: In the Mercur mine, Mercur district, Utah, there is a system of open cracks and fissures, cutting the limestones and also traversing a system of calcite veins, later in age than the limestone, but earlier than the fissures. These cracks often follow the course of a calcite vein, which evidently offered less resistance than the limestone. Even where the vein and the fissure are perpendicular one to the other, the latter is often deflected by the former (Fig. 41). The accompanying sketch is from the wall of a tunnel in the Mercur mine.

Again, the visible crack which we call a fracture may be a combined series of joints or fractures, each approaching a

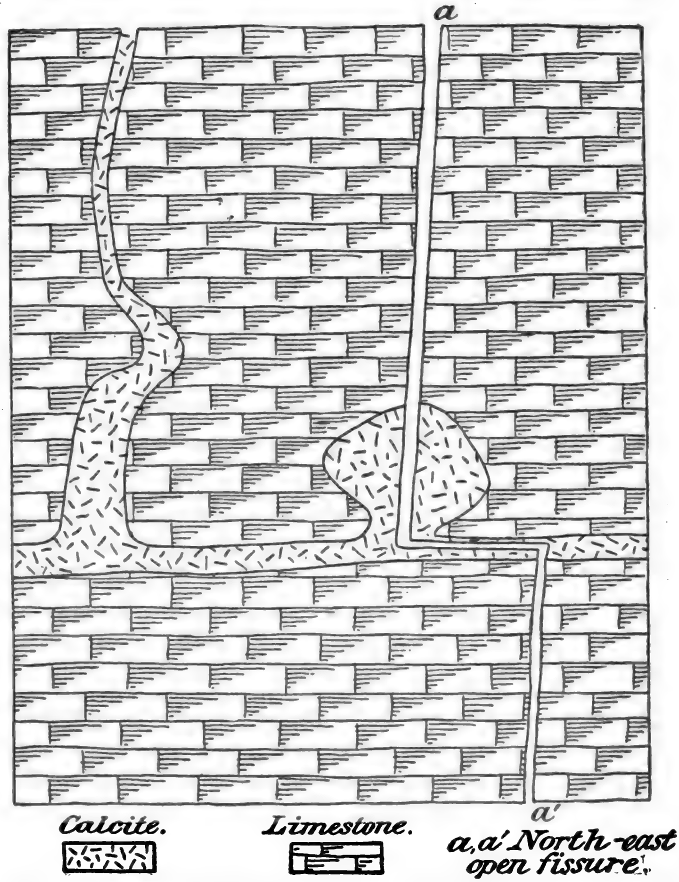

Fig. 41. Open fissure cutting and deflected by calcite vein, Mercur mine, Utah After J. E. Spurr.*

mathematical plane, but together having an irregular course.

* 16th Annual Report United States Geological Survey, Part II, p. 409.

How do fractures behave in different stratified rocks?

In non-homogeneous rock, as has been pointed out, fractures, from whatever initial stress they may arise, will tend to be deflected in the direction of least resistance. In thin beds of homogeneous rock, such as a dense sandstone or limestone, this direction is apt to be directly across the bed, perpendicular to the stratification.

In a shale, on the other hand, the fracture will tend to be deflected in the direction of the bedding, and in slates in the direction of the cleavage. A fracture may entirely cease on encountering a transverse fracture, the movement being deflected and taken up by the latter.

Fractures are naturally most clean cut and persistent in rigid rocks, like quartzites and igneous rocks. In soft rocks like shales, any movement arising from stress may be partly or wholly taken up by the yielding of the rock near the disturbance, a giving way analogous to flowage.

Therefore, in passing from one stratum to another, such as from a sandstone into a shale, fractures often change both in direction and intensity. A strong fracture in a sandstone bed may die out entirely in passing into a shale.

Are fractures and joints always persistent even in rigid and homogeneous rocks?

Fractures, joints and faults may become less, and even die out in rigid strata, where there is, nevertheless, enough yielding progressively to take up more and more of the dislocation.

What are imbricating fractures?

It frequently happens that when a fracture stops, the continuation of the same line of weakness is shown by a parallel fracture, a little to one side, beginning near where the other leaves off, or overlapping. These may be called imbricating fractures.

How are open fissures formed near the surface?

Even in greatly disturbed, folded, faulted and jointed rocks, open fissures, larger than cracks, are relatively rare and unimportant. At the very surface, the shrinkage of volume in rocks resulting from chemical changes, and the falling apart under the influence of gravity, cause many fissures. But these conditions are characteristic only near the surface. The rock encountered in mines is much more solid.

Example: The granite rocks of Cape Ann, Massachusetts, especially as exposed along the shore, are traversed by many open joint fissures and by joint fractures (Fig. 42). At a very little distance below the surface, however, the fissures disappear, and the fractures diminish greatly in frequency, so that the rock found in quarries is a good building-stone.

How are openings below the surface formed, and to what depth do they persist?

Fissures encountered in mines are not usually produced directly by dynamic action, but are due to the dissolving action of underground water circulating along faults, fractures, or shear-zones. In easily soluble rocks, like

Fig. 42. Granite quarry, showing increase of fractures and fissures near the surface. Rockport, Massachusetts. After N. S. Shaler, 9th Annual Report United States Geological Survey.

limestones, openings made in this way are especially large, and a series of irregular connecting caves may result. In less soluble rocks, solution will generally not produce caves, but only irregular widenings of the original crevice; the resulting water channels will be straighter than in soluble rocks, but will open out at one place, and contract almost to nothing at another. In the case of the soluble rocks, open spaces are due almost wholly to solution; in the case of the difficultly soluble ones, the same may be the case; but in neither would the water have ordinarily been able to gain access, so as to accomplish its dissolving, without some preliminary channel due to rending. One can put it as an almost invariable rule, therefore, that fissures are not open and regular for long distances. They are rather a string of connected openings of limited extent. This is necessarily true, for a regular open fissure any distance underground would soon be closed by the effects of gravity. Irregular openings, with buttresses of solid rock between, supporting the weight on both sides, can and do remain open to considerable depths. At a certain ultimate depth, however, it is supposed that the great pressure (combined with increased fluidity of the rock, due to increase of temperature) is sufficient to close even openings of this sort.

Deposition of Ores Along Fractures and Fissures.

What is the application of the study of fissures and fractures to the study of mineral veins?

Fractures and fissures become the channels for circulating

waters, and the seats of vein formation. Each one of their characteristics, therefore, is characteristic also of a certain class of mineral veins.

Do the veins in a given region ever follow definite systems in regard to their trend?

Fractures and fissures, it has been pointed out, often result from a regional strain in the crust, affecting large areas alike. They are, therefore, formed in definite systems, and where they become mineralized, the veins fall into similar groupings.

Example: In the southwest of England, a series of fissures running north and south, or north-northwest and south-southeast, traverses another series which runs in a more east-and-west direction. The latter in Cornwall contains the chief copper and tin ores, while the former contains lead and iron. The east-and-west veins in the west part of the region were formed before those that cross them, for they are shifted, and their contents are broken through by the latter.*

What bearing has the irregular course of fractures on mineral veins?

Mineralizing waters follow along fractures in all their deviations. Along their course they often deposit ore, both in the fractures and in the rock, by cavity-filling, replacement or interstitial filling (impregnation).

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* De La Beche, 'Geological Observer,' p. 659.

Example: Many of the ore-bodies in the Tintic district, Utah,* furnish excellent examples of veins formed along circulation channels offered by successive fractures running in different directions. The accompanying figure is from the Ajax mine in that district. The country rock is limestone, and the ores (which consist chiefly of pyrite, galena, and enargite, carrying gold and silver, oxidation products of these sulphides, and quartz and barite as gangue minerals) have been deposited as replacements of this rock, in the neighborhood of the fractures. The fractures as a rule are continuous past the point where they cease to be ore-bearing, though this is not well represented in the diagram (Fig. 43). This type of vein is an important and common one, and grades into very irregular ore-bodies.

Does the peculiar behavior of fractures and joints in different stratified rocks find an analogous behavior in mineral veins?

Mineral veins in different kinds of stratified rocks show a variation which corresponds exactly to the variations of fractures under like circumstances.

Example: In the Bendigo gold-fields, Australia, the auriferous quartz veins, largely in sandstone and shale, show many irregularities illustrating these points. Fig. 44 shows the cross-section of an open cut behind the Victoria Quartz mine in this region. Here is seen how veins in the standstone stop abruptly on reaching the shale; how others, stronger, persist into the shale, but are deflected in

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* G. W. Tower, Jr., and G. O. Smith, 19th Annual Report United States Geological Survey, Part III, p. 724, *et seq.*

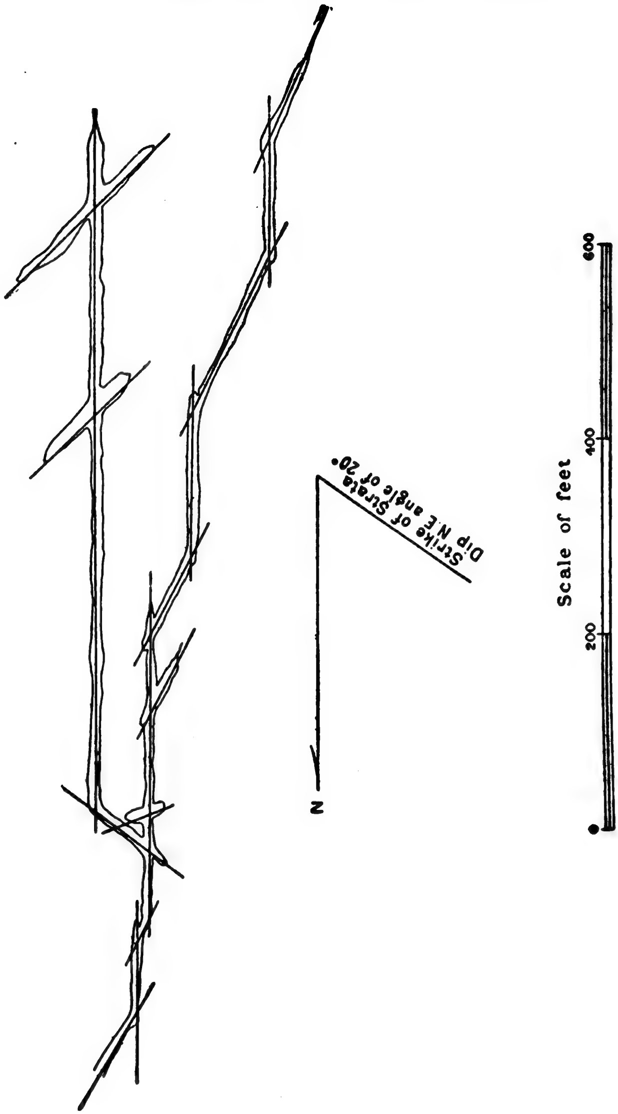

Fig. 48. Diagrammatic plan of ore-bodies, Ajax mine, Tintic district, Utah. The straight lines are joints, the areas of irregular outline, ore-bodies. After G. W. Tower, Jr., and G. O. Smith.

the direction of the bedding, and finally die out. The deflections of veins in sandstone, passing through a slate bed, is further shown in Fig. 45, from the same district.*

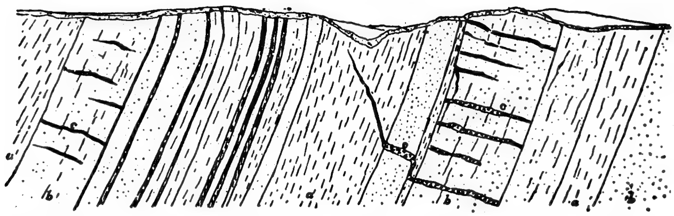

Fig. 44. Open cut of Victoria Quartz mine, Bendigo, Australia. *a*, slate; *b*, sandstone; *c*, gold quartz veins. After T. A. Rickard.

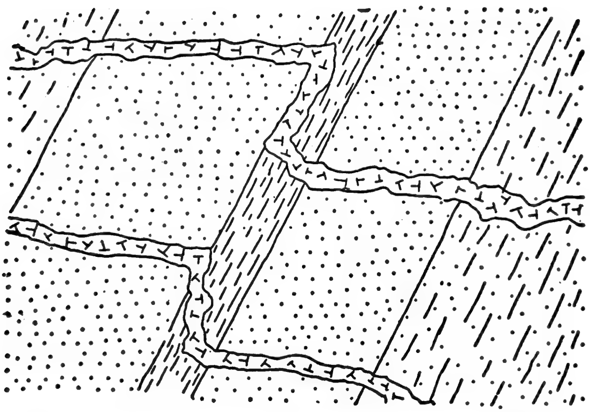

Fig. 45. Quartz veins in Confidence Extended mine, Bendigo, Australia. After T. A. Rickard.

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* T. A. Rickard. 'The Bendigo Gold Field,' (Second paper). *Transactions* American Institute Mining Engineers, Vol. XXI, pp. 686-713.

Does the increase in the number and size of cracks and fissures close to the surface have an influence upon mineral veins?

The cracks and fissures near the surface, opened up in the manner previously described, very frequently become the channels of mineralizing waters, and the sites of ore-deposition, and are thus transformed into mineral veins. Such veins, following the characteristics of the joints, fractures or fissures along which they were formed, will be largest and most numerous at the surface. Below the surface they will become less in number, and will tend to unite, forming a smaller number or even a single well-defined strong vein, which persists to a considerable depth. This occurrence is a matter of common observation among miners, who often remark that a vein is "all broken up" near the surface, and that it will get "more regular as it goes down."

Under what conditions are branching surface veins, like those described, formed?

It follows, from the method of origin of the fractures in which the veins were deposited, that the ores were brought to their position and there laid down at a very slight distance from the surface. The waters which are active close to the surface are descending atmospheric waters, and in a case of this kind it is usually these which have formed the veins. The fewer and more regular veins attained in depth are frequently the product of an earlier period of deposition, which the surface waters have worked over and re-deposited to form the surface ores, as will be explained in the next chapter.

What are filled deposits?

Veins or ore-bodies deposited in pre-existing cavities, (not microscopic), whether caused by rending or solution (generally by both) may be called filled deposits.

What is crustification?

Crustification is a banded structure produced by successive deposition of different layers on the walls of an opening; it is often visible in filled deposits.

Do all filled deposits show crustification?

Many deposits which have formed in open cavities show no banding, but an irregular arrangement of minerals, or are massive and homogeneous throughout.

Is all banding in veins, parallel to the walls, crustification?

Replacement deposits may often show banding in all degress of perfection, sometimes simulating almost exactly the crustification of filled deposits. This arises from the existence of bands of different texture or chemical composition in the original rock. Certain of the bands may induce the formation of a particular mineral during the process of replacement, or at any rate may cause differences of texture, even if the minerals deposited in the different bands be approximately the same. Along fracture-zones or shear-zones a very perfectly banded ore-deposit may form by replacement, for the parts along the fracture planes are replaced first, and afterward, more slowly and under different conditions, the rock space between the planes. This results in either physical or chemical differ-

ences, which are plainly visible as bands. Again, the fracture crevices may be filled with vein matter, and the sheets of rock between may be mineralized by the replacement process; and thus a banded appearance results.

Example: According to S. F. Emmons there is in many of the ore-deposits in the Gunnison region, in Colorado, a noteworthy appearance of banded structure parallel with the walls. Yet the evidence of thin sheeting of the country-rock is so clear that it is probable this appearance arises from the fact that some of the bands are the filling of narrow fissures, and others a replacement of thin sheets of the country-rock, the differing composition of the bands resulting from the variation in the process of deposition.

Ribbon structure, described on p. 199, as a sheeting produced parallel to the walls of a vein, by movement subsequent to its formation, may also be mistaken for crustification.

What is a fissure vein?

The best type of the filled deposit is the fissure vein, which may or may not show crustification. Such a vein is characterized by regular, straight walls, by a fairly constant width, and by a definite direction of both strike and dip. There is usually a sharp line of division between the vein and the wall rock, such as is generally wanting in replacement deposits.

Do ore-deposits in pre-existing cavities always form a distinct class from other deposits?

Ore-deposits which have filled pre-existing cavities may

also extend into the wall rock of the fissures, by replacement or impregnation, and often no line can be drawn between the ores formed by one process and those formed by another, the two sorts forming a continuous body.

What are linked veins?

Linked veins are the filling of a series of branching and reuniting fractures, of a peculiar type which can be best shown by illustration (Fig. 46).

Fig. 46. Linked veins. Surface plan of vein system of Pachuca, Mexico. Scale 1=50,000. After E. Ordoñez.

Example: In the mining district of Pachuca, in Mexico, the veins follow a general east-west course, and are united by diagonal branches. The peculiar character of each branch is that it never crosses the veins that it unites.

Often two branches start from a vein at the same point and run in opposite directions, so that one is apparently the prolongation of the other; this circumstance has led some miners to the belief in the crossing of the branches, and has led them into serious mistakes.*

SHEAR ZONES OR CRUSHED ZONES, AND THEIR SUITABILITY FOR ORE-DEPOSITION.

What are shear zones or fracture zones, and what influence have they on ore-deposition?

When a rock mass is put under pressure by earth movement, some parts of the rock, being weaker, will yield and will be crushed, bent and broken to a greater extent. These areas are apt to be fairly regular, and generally they form pretty well defined zones of variable thickness, often with obscure walls between them and the more solid rock. If there has been movement along such a crushed zone, so that the rock on one side has changed position noticeably with the rock on the other side, it becomes a fault or a fault zone. Often, however, there is hardly any noticeable faulting, and in this case we may call it a shear zone, if the rock has been crushed and sheared, or a fracture zone, if it has only been especially intensely fractured. In either case such a disturbed area or zone offers a channel for circulating waters, and is very favorable to ore-deposition, for the comparative slowness of circulation enforced by the obstructed passage makes the percolation thorough, and offers every chance for precipitation.

* E. Ordoñez, *Boletin* del Instituto Geologico de Mexico, 'El Mineral de Pachuca,' p. 57.

Example: The gold-quartz veins of Otago, New Zealand, described by T. A. Rickard*, have formed largely in shear zones, and the lodes show every variation from a condition where the country rock (schist) forms the greater part, to the entirely replaced stage, where the vein is clear auriferous quartz. They are found in channels but little divided from the main mass of the country rock, and the schists themselves, beyond the lode boundaries, are often auriferous. Probably certain belts of the schist, outside of the lodes, are sufficiently mineralized to become mines.

GENERAL RELATION BETWEEN ROCK DISTURBANCES AND ORE-DEPOSITS.

Are regions of undisturbed rocks favorable for ore-deposits?

In general a region of flat unfolded rocks is poor in ore-deposits, as for example the region lying between the Rocky Mountains and the Appalachians, as compared with the folded region lying between the Rocky Mountains and the Pacific. Where ore-deposits do occur in such a flat region, they will often be found to be connected with some minor disturbance.

Example: In southern Missouri and adjacent parts of Kansas and Arkansas, the flat Paleozoic strata, together with underlying ancient crystalline rocks, have been affected by a monoclinal uplift, elliptical in outline, known as the Ozark uplift. On the summit the bedding planes are horizontal, while throughout the border areas they are inclined away from the center. This disturbance has produced fracturing, more pronounced along the

* *Transactions* American Institute Mining Engineers, Vol. XXI, pp 411-442.

borders than on the tops, and the principal mining localities (producing lead and zinc ores) are situated around this border in such a way as to indicate that the mineralization has been dependent upon the fracturing. In this case the mineralization is thought to have been brought about by descending waters, and not to have been connected with igneous rocks or hot springs.*

What is the reason for the general connection of ore-deposits with disturbed rocks?

Mountains, igneous rocks, folded strata, hot springs, and ore-deposits are often all connected. The zones of folding in strata lie along certain lines of weakness in the crust. The relief of pressure caused by the giving away of the strata in the folded region may cause a migration of the suppressed molten rock beneath the crust to this zone; eruptions and intrusions, accompanied by further disturbances, follow. Fractures and fissures are formed; by the influence of the igneous rocks hot spring action is set up; and the igneous rocks themselves contain disseminated metals which they supply to the circulating waters. As a consequence of part or all of these conditions various kinds of ore-deposits result.

THE INTERSECTION OF CIRCULATION CHANNELS AS SEATS OF MINERALIZATION.

What are ore-shoots?

Veins or lodes are not usually equally rich throughout. Poor or barren spaces of lode separate ore-bodies irregular

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* E. Haworth, *Bulletin* Geological Society America, Vol. II, pp. 231-240.

in form or having more or less roughly a columnar shape. The latter are called ore-shoots or chimneys (Fig. 47).

What is the principle of intersection as regards ore-deposits?

A large proportion of ore-shoots is formed by the intersection of two water-courses. This may mean the intersection of two faults, of two joints, of a joint with a fault plane, of joints or faults with a porous stratum, etc. The

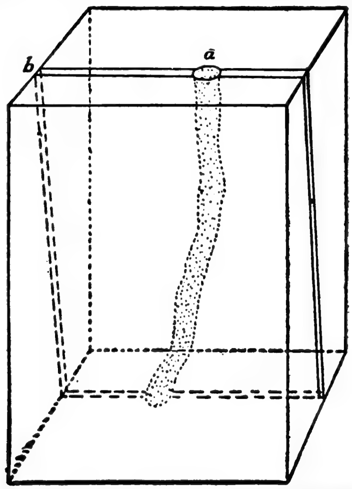

Fig. 47. Ore-shoot in Annie Lee mine, Cripple Creek, Colorado. *a*, ore-shoot; *b*, dike in which shoot lies. After R. A. F. Penrose, Jr.*

principle is nearly the same throughout, and is explained in Chapter V. It is at the intersection of two circulation channels, whether now or only formerly used by the solutions, that one may look, in almost any district, for the richest ore-bodies. In well-defined veins, the pockets or richest portions are apt to lie at the juncture of the main vein with subordinate intersecting fractures or veins (feeders).

* 16th Annual Report United States Geological Survey, Part II.

ROCK MOVEMENTS SUBSEQUENT TO ORE-DEPOSITION.

Do rock movements occur subsequent to ore-deposition?

In some cases we find a vein or ore-deposit entirely unaffected by movements of the rocks after its deposition; but generally there has been some subsequent disturbance, producing folding, faulting, shearing, jointing, fracturing, and fissuring, which affect the ore-body in the same way as the enclosing rock. These movements may be very slight, or they may be profound.

How do subsequent movements diminish the value of an ore-body?

The bending, breaking and separation of the parts of an ore-body or vein may make it difficult to follow it in mining; or so expensive that the profit will not pay for the labor involved; or, sometimes, practically impossible.

Do movements subsequent to ore-deposition always decrease the value of a vein or other ore-body?

Sometimes the disturbances may have an effect beneficial to mining. The folding and faulting may so displace the ore-body as to make it more accessible to mining operations than it otherwise would be. Take the case of a coal or an ore-bearing bed, for example, which dips steeply into the earth. The deeper such a bed is followed, the more expensive and difficult becomes the mining. But if it is folded and faulted so that it comes to the surface in a number of different places, then it can be easily worked at each of these.

Dislocations Subsequent to Ore-Deposition as Seats for Later Mineralization.

Is the foregoing the only way that movements subsequent to ore-deposition operate to increase the value of a vein?

An ore-body may be traversed by joints, or fissures, which afford channels for waters to circulate, where otherwise the openings have been completely cemented by ore and accompanying gangue. These new openings may be in time partially or wholly cemented up with gangue, or with ore and gangue, and frequently the waters will work over the old ore and reprecipitate it in concentrated form, both in the fractures and in the vein near by. Thus these portions may become the richest in the vein, and perhaps the only portions that it will pay to work. Many ore-shoots are of this origin. Again, the new solutions may bring fresh metals from some outside source, which they may deposit in or near the new fractures, either adding them to the earlier deposited metals or depositing them independently; and in this way also richer bodies may be formed in the older vein.

In what direction are the subsequent fractures most likely to occur with respect to the original veins or shoots?

Movements in rocks are likely to be very long continued, though intermittent; and planes or zones of weakness being once formed, renewed movements are likely to take place along them. The openings along which ores are formed are planes or zones of weakness, hence movement may occur along them while the first deposition

is taking place, or after it has closed. Even though the opening has been entirely cemented up by ore and gangue, the regions of weakness will often remain as such, because the parallel parting planes of the veins and the encasing rock preserve the original slip-surfaces, and because the brittle quartz, calcite, etc., of the vein may be in many cases more easily broken than the tougher and more yielding rock. Therefore, movements subsequent to ore-deposition are very likely to fracture the veins parallel to their course, the fractures either lying in them or alongside of them; and are also likely to renew the fractures whose intersection with the main original fracture and vein zone gave rise to ore-shoots. In this way later parallel bands in the main vein, of different character (both as regards mineral composition and value), may be produced; and the old shoots may be enriched by a second deposition.

Ribbon Structure.

What is ribbon structure?

Movements in veins subsequent to their formation may produce a sheeting parallel to the walls, which may have somewhat the aspect of original crustification, and may be mistaken for it. This sort of banding is called ribbon structure.

Example: The gold-bearing quartz veins of Nevada City and Grass Valley, California, typically show sheeting or ribbon structure, due to movement since deposition. True original banding, or crustification, is also found in these veins, and often occurs in the same specimen of rock as the

ribbon structure. Fig. 48 is a photograph of a specimen of vein quartz containing gold-bearing pyrites from the Providence mine.

FAULTED FAULTS AND THEIR RELATION TO ORE-DEPOSITION.

Are the faults of one period ever faulted by the faults of a later period?

Where there are a number of faults, developed at different periods, the later movement may take place along the same plane as the older one; thus along an old break the new disturbance will continue the faulting and increase it. Fault fissures which have become occupied by ore-bearing veins often experience such renewal of motion, and we find evidence of it in the crushed ore and vein material, which may subsequently become re-cemented by new mineral deposition, and yet will always show the angular outlines due to breaking.

Again, the later faults may be developed along planes not parallel to the old ones, and so cut and displace the old faults in precisely the same way as the enclosing formation. Where ores have formed along both the earlier and later faults, one vein may be found faulting another.

A specially complicated and likely case is where faulting goes on for a long period slowly, and contemporaneously with a persistent process of ore-deposition. The first ore-deposits may be subsequent to the first folds and faults, but they will be disturbed by the later movements; yet these later faults may be chosen for the seats of newer ore-deposits, which may again be broken by still more recent movements,

Fig. 48. Vein quartz, showing ribbon structure; from Providence mine, Grass Valley district, California. After Waldemar Lindgren.*

* 17th Annual Report United States Geological Survey, Part II, Pl. IX.

and so on. In such cases only careful examination of the phenomena connected with each separate ore-deposit can determine its age relative to the various displacements, and serve as a guide to mining operations.

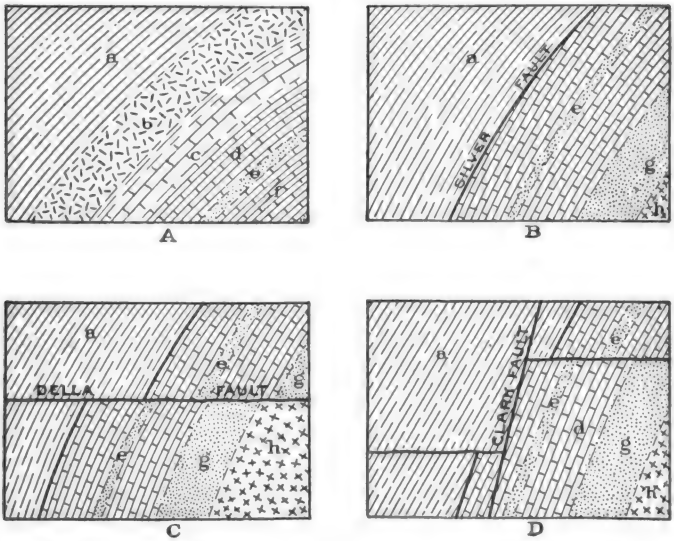

Fig. 49. Faulting in Smuggler and Molly Gibson mines, Aspen, Colorado. ***a*, Carboniferous shales; *b*, porphyry (intrusive sheet); *c*, Carboniferous limestone; *d*, Carboniferous dolomite; *e*, Devonian quartzite series; *f*, Silurian dolomite; *g*, Cambrian quartzite; *h*, Archæan granite. After J. E. Spurr.**

Example: A good example of successive faults acting in different directions is found in the Smuggler and Molly Gibson mines, Aspen, Colorado.* Study of the geology here shows that first the rocks were folded and acquired a steep dip (Fig. 49). Next came the development of the Silver fault, nearly parallel to the bedding, but of such great

*** J. E. Spurr, Monograph XXXI, United States Geological Survey, pp. 181-188.**

displacement as to cut out the porphyry sheet *b* and the limestone *c*, so that the shale *a* was brought into contact with the dolomite *d* (Fig. 49 B). Subsequently came a series of east-west faults dipping to the south (such as the Della fault) which faulted the Silver fault together with the rock formations (Fig. 49 C). Finally there came a slipping on the old plane of the Silver fault, which locally deviated from that plane, and so constituted an independent fault (Clark fault). The final result is shown in Fig. 49 D. The Silver fault was formed before ore-deposition; the Della fault began to form before ore-deposition, but continued after it. The Clark fault was formed after the main ore-deposition, yet secondary more recent ores have, to a slight extent, formed along it.

ROCK MOVEMENTS ALONG EARLIER-FORMED DIKES.

Why do veins sometimes form along earlier-formed dikes?

Following up the principle indicated in the foregoing pages, we may remark that dikes of igneous rock are usually intruded along lines of weakness in the rocks which they cut. In the same way as mentioned in the case of veins, the zone of weakness, though to a certain extent cemented by the dike, is still apt to remain weaker than the rest of the rock. Any renewal of the strains, therefore, is likely to produce a renewed fracturing along this line, creating a new channel, which may become the passage of circulating waters and in this way be again cemented (this time by water action), and become a mineral-bearing vein. The contact of the dike with the fractured country rock is usually the weakest line; hence, later veins are apt to occupy this position.

Example: The Black Jack-Trade Dollar vein, De Lamar district, Idaho, consists of a quartz and orthoclase-feldspar (valencianite) gangue enclosing rich silver and gold minerals in small quantities. The lower part of the vein is situated at the contact of granite with a basalt dike a

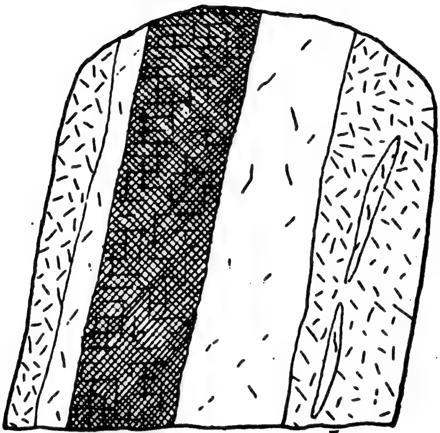

Fig. 50. Vein following the course af a pre-existing dike Trade Dollar vein, De Lamar district, Idaho. *a*, basalt dike; *b*, granite; *c*, vein quartz. After W. Lindgren.

few feet in thickness. The vein is separated from the basalt by well-defined walls and gouge, and often shows comb-structure.

There is evidence that fracturing and faulting have taken place at the contact of the granite with the basalt dike, involving a horizontal throw of 125 feet. Thus the old fracture zone, which existed before the advent of the dike, was reopened, and gave passage to waters which deposited the vein* (Fig. 50).

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* Waldemar Lindgren, 20th Annual Report United States Geological Survey, Part III, pp. 144, 165, etc.

PART III.

PLACERS.

Why are placers considered under the head of dynamic geology?

To dynamic geology belongs not only the study of rock movements beneath the crust, but also those on the surface. Thus under this head we naturally take into consideration stratified ore-deposits, so far as these are chiefly of mechanical origin.

The most important class of stratified deposits are the placers. The name placer is applied to detrital deposits of metals or valuable minerals, especially gold.

THE CONCENTRATION OF GOLD IN PLACERS.

What is the origin of placers?

Rocks at the surface are broken up by erosion and find their way, by the power of gravity, aided by running water, down into the valleys. In the highest valleys only the coarser fragments remain, for the streams carry away the smaller ones. Further down, as the stream current loses its force, some of these smaller ones are deposited, and only the still finer material is carried on, until nothing but silt or mud is left. In a gold-bearing region, the veins are broken up and sent on their journey in company with the detritus of the enclosing rocks.

CONCENTRATION BY CHEMICAL WATER-ACTION.

How is gold freed from associated baser metals, in the surface outcrops of veins?

Gold, in deposits not too close to the surface, generally occurs in small quantities in intimate association with metallic sulphides, such as pyrite (iron sulphide), galena (lead sulphide), arsenopyrite or mispickel (sulph-arsenide of iron), these sulphides being contained in quartz veins. Near the surface, atmospheric agents attack the veins chemically, and, if erosion is slow enough to let these agents exercise their full influence in decomposing, dissolving, carrying away and re-depositing the various constituents, the result is that the surface portion comes to have a different character from the deeper part. The sulphides are broken up and taken into solution; and the metals thus dissolved are either carried quite away or are re-deposited in deeper parts of the vein. But gold is soluble with much greater difficulty than most other metals; hence, when the sulphides which contained it are dissolved, it is mostly left behind, in its native state, as free gold.

How is gold purified and chemically concentrated?

Where the surface rocks are decomposed, the gold, mixed with the débris produced by erosion, may then be already in the free state. Frequently, however, the sulphides outcrop, or the gold is imperfectly separated from other materials. Then in the gravels exactly the same process goes on as we have described as occurring in the vein outcrop, and (on account of the great porosity of the

gravels, permitting atmospheric waters to attack freely every part), the baser metals are carried away in solution, and the gold is left behind or is dissolved and re-precipitated. This is one reason why so much of the gold in placers, when examined microscopically, shows unscratched or even crystalline surfaces, indicating chemical deposition. Fragmental pieces of gold may receive fresh coatings from solutions thus originating; or the solutions may deposit gold upon fragments of organic matter, or metallic sulphides, for these substances exert a precipitating effect.

It is even probable that gold already deposited in the native state may be, to a slight extent, re-dissolved and re-arranged.

Some observers, seeing the evidence of this chemical action in placers, have concluded that gold might be introduced into the placers from other localities, in solution in surface waters. But it seems certain that the ruling influence is mechanical, and that chemical influence is only auxiliary, producing further concentration and rearrangement.

Why do gold placers often occur near mines containing chiefly other metals, such as silver, lead, copper, etc.?

The fact that from all the metals carried from a vein to the gravels, only gold survives, the rest being more or less fully removed in solution, explains why many rich silver regions, such as the Comstock and Leadville, were first worked for their gold-bearing gravels. The ores carry a certain proportion of gold, and it is this, freed more or less completely from the other metallic constituents of the

ore-deposits, which becomes placer gold. Even ores containing only traces of gold may thus give rise to gold-bearing gravels.

Concentration by Mechanical Water-Action.

How is gold mechanically concentrated in placers?

Particles of native gold in gravels, brought down into the valleys by mechanical action, and freed from other metals and often increased beyond their original size by chemical action, are in the valleys still further mechanically concentrated. Waters shift the gravels so that the heaviest minerals, especially the gold, sink naturally to the bottom; and, where there is not much disturbance by running water, the gold particles seem to be able to work downward through the loose gravel, probably during such movement as the deposit undergoes from percolating waters, or from alternate thawing and freezing.

What is the pay-streak in gravels?

The result of the downward sifting of the gold is that where the valley-deposits (sand, gravel, etc.) are porous, by far the greater quantity of gold will be found at the very bottom, in the few inches overlying the bed-rock. This is called the pay-streak.

How is it that gold is often found in the bed-rock, under the gravel?

The bed-rock itself, (especially if it is a shale or a schist, and so affords cracks for the gold to work itself into), is

commonly rich for several inches in depth, and is taken up by miners and worked with the gravels. This fact sometimes leads to the belief that the gold was originally contained in these rocks; but generally the rock a little distance below the surface will be found entirely barren, disproving this supposition.

Why is the gold not especially concentrated in the pay-streaks of certain placers?

Where the gravels are not sufficiently porous, the gold cannot work itself down so well, and as a result it may occur scattered throughout the whole deposit, though in this case the gravel is relatively poorer per cubic yard than the pay-streak on the bottom of porous gravels, the amount of gold which is usually concentrated in the pay-streak being distributed throughout the mass.

What is a false bottom, and how may it cause a second pay-streak?

When there is, in the deposit, an impervious layer, such as a clay seam, this will arrest the downward working of the gold, and above it a pay-streak will be formed. A lava bed, or a solid conglomerate, may play the same part. Such an impervious layer is often called the false bottom. from having the appearance of being the base of the gravels. There may be several of these, with intervening gravel beds, one below the other, each overlain by its pay-streak; beneath, the real bottom may also have its pay-streak.

Example: Quartz creek, Seward Peninsula, Alaska, contains gold-bearing gravels on its bottom and sides (Fig. 51). The gold now (1900) being mined lies 2 or 3 feet below the surface, on what the miners call the bed-rock, which is a blue clay, apparently intercalated in the gravels. This blue clay afforded a floor upon which the gold was concentrated. The real bed-rock at this point has not been reached.

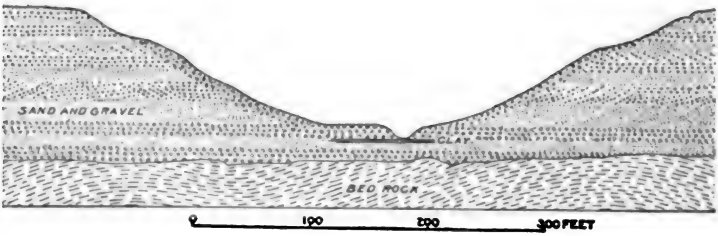

Fig. 51. False bottom of clay in a gold placer deposit. Cross-section of Quartz creek, Kugruk, Alaska. Adapted from A. H. Brooks.*

What is the origin and signification of black sand and ruby sand in gravels?

By the natural process of concentration other heavy minerals are also collected, but, as none of them are so heavy as gold, they are concentrated to a less degree. The magnetite which is present in many rocks is concentrated, and becomes the black sand or magnetic sand of miners; the garnets found in many schists and other metamorphic rocks form the ruby sand, etc. So, when a miner washes a pan of gravel and gets a little black sand, his experience generally tells him that the chances of gold are small, the

* United States Geological Survey, 1901, 'Reconnaissance in Nome Region,' etc., Fig. 2.

exact reason being that the materials in this gravel have not been concentrated. In many regions the auriferous veins are in rocks containing garnet; and the prospector rightly concludes that the presence of ruby sand is a favorable sign. On the other hand, the presence of either of these sands does not necessarily indicate even a small quantity of gold.

Effects of Glacial Action.

What foundation is there in the theory often held by miners, that glaciers are responsible for many placer-deposits?

Frozen water, (snow, and especially ice), is a powerful erosive agent. It fills crevices in rocks, and by its expansion in freezing rends them apart; it accumulates in masses on the steep hill sides in high mountains as mountain glaciers; it moves down into the valleys as valley glaciers; or, finally, piling up over mountain and valley, it forms a great ice cap, or continental glacier. The slowly flowing ice grinds away the rock on its bottom and sides, and carries along on its surface what slides down on it from cliffs above. So in glacier regions there is generally a much greater abundance of surface débris than in unglaciated ones. It may be, therefore, that glaciers are often effective in breaking up auriferous rocks; but the cases where profitable placers are due entirely to glacial action are probably few. This remark is made because it is a favorite theory with miners "that the gold was brought down by glaciers." Placers often occur in districts which do not have any glaciers and never had any. It is true

that many regions now bare of glaciers were formerly covered with them, such as the great glaciated areas of Canada and the North Eastern United States; but in each place we must find the characteristic mark of glacier deposits—unstratified drift or "till," ice scratches, glacial topography, etc.,—before we can allow this factor to even become possible in any theory of placer formation.

Besides the ground-up, unstratified drift which is the product of the glacial mill, streams derived from the melting of the glaciers, coming from their surface and below, work over, rearrange and deposit the drift in more or less stratified form. Such action tends to classify the minerals present, but the process is generally incomplete as compared with that accomplished by streams in valleys. Hence, even stratified glacial deposits are not very favorable for placers.

Nevertheless, ordinary streams may take up material supplied by glacial action and by "classifying" it so as to shake the gold down to the bottom, produce good placers. In some cases, even, the material ground out of auriferous rocks by glaciers, and worked over by glacial streams, may be rich enough in concentrated gold to be valuable.

Example: The Blue Spur placers, in the Otago district, New Zealand, have been described by T. A. Rickard,* who considers them due to the combined action of glacial ice and glacial water. The deposit is probably as old as the Eocene period, and belongs to the class of old placers,† being above the bed of the present streams.

* *Transactions* American Institute Mining Engineers, Vol. XXI, pp. 432-436.
† See p. 222.

The depression in which the auriferous gravels rest is not that of an ordinary river valley, but is rather an irregular cup-shaped depression in the schist (Fig. 52). In the bottoms and sides of this hollow there are also other smaller hollows in the bed-rock, such as are not usually

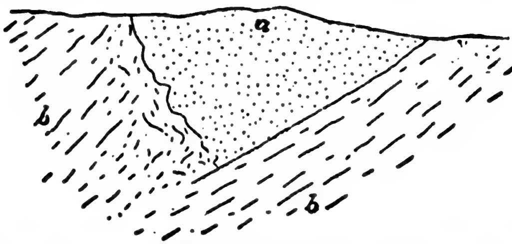

Fig. 52. Basin containing auriferous glacial gravels. Blue Spur placers, Otago district, New Zealand. *a*, auriferous gravels; *b*, schist. After T. A. Rickard.

formed by running water (Fig. 53). Therefore, the basin is believed to have been scooped out by a glacier, to which conclusion the occurrence of large boulders in the deposit, derived from a locality 25 miles distant, lends support.

After scooping out the depressions, the glacier is sup-

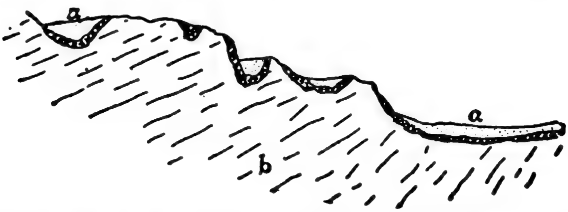

Fig. 53. Irregular depressions filled with auriferous glacial gravels. After T. A. Rickard.

posed to have retreated, leaving the hollows to be occupied by a lake. Materials ground out of the auriferous schists by the glacier in the new position were carried into the lake, where they accumulated in thick, coarse, rudely stratified deposits. The gold gradually sifted its way to

the lower portions. These deposits are now transformed into hills by the erosion of streams, which first drained the lakes, and then cut down through the lake sediments.

VARIOUS KINDS OF STREAM GOLD PLACERS.

What are gulch placers?

Gulch placers are formed in the highest narrow valleys, or gulches, of a river system. They usually head in hills or mountains, and the material in their bottoms, though rudely stratified, is coarse and shows only slightly the effects of wear and transportation. In the extreme upper portion of the gulch, where it heads in the bed-rock, gravel is often wanting, but the amount of it increases as the gulch gains depth. The gulches are generally more or less V-shaped in outline; hence the width of the deposit is slight. The gold, being near its place of origin, is comparatively coarse. The relative richness of various gulches, even neighboring ones, varies greatly, according to the richness of the rocks through which they cut.

Example: Myrtle creek, Koyukuk district, Alaska, may be selected at random from a host of examples. The gravels here rarely exceed 3½ feet in thickness, and overlie mica-schist and slate, which stand on edge. The gold is found principally on or near bed-rock, in the joints, fissures, and cleavage crevices (Fig. 54).

What are the characteristics of broad valley placers?

The upper valleys or gulches unite further down to form larger and broader valleys. Here the stream flows in a level plain of gravelly materials, which stretches back to

Fig. 54. Gulch placer on Myrtle creek, Koyukuk district, Alaska. After F. C. Schrader. 21st Annual Report United States Geological Survey, Part II, Pl. LXVII.

the valley sides. As the stream wears away one bank and builds up another, it changes its position, and so, at one time it runs along one side of its valley, and at another time the opposite side. In this lateral swinging it works over, classifies and smooths the gravels of its flood-plain. In auriferous regions these gravels become placers.

The valley gravels are in far greater quantity than the gulch gravels; and, since with increasing distance from the head of the stream the gradient of the stream usually decreases, permitting increased deposition, their thickness is comparatively great. On account of the more complete work of the swinging rivers, the gold content is apt to be more uniform than in the gulch placers; and since not only the rich but the barren gulches have contributed their material, this content is apt to be considerably less than the rich but limited gulch placers.

Where is the most gold apt to be found in valley gravels?

Although valley placers attain often to a considerable depth, the statements made above concerning the working downward of the gold in gulch placers, by reason of its gravity, seem to apply here also.

Is the gold of broad valley placers of the same kind as that in the gulch placers?

Naturally, in broad valley placers the gold is generally of finer size than in the gulches.

What are bar placers or bar diggings?

When a stream runs through auriferous gravels and by

undercutting its banks brings down and works over large quantities of these gravels, the gold undergoes a further

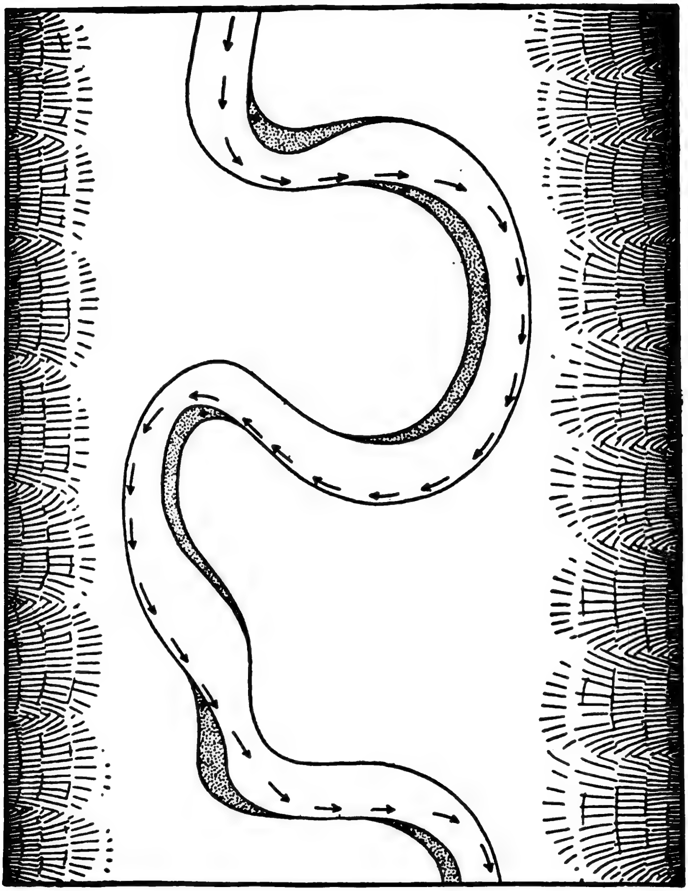

Fig. 55. Diagram of ideal river, showing accumulation of bars. Crosses show the most favorable spots for the deposition of gold. After J. E. Spurr.*

concentration in the stream current. At places where the current slackens to the right point, the heavy gold and the

* 18th Annual Report United States Geological Survey, Part III, Fig. 24.

coarse pebbles are deposited; further on, the fine gold and the smaller pebbles and sand. On such a river "colors" (small flakes) of gold may be found everywhere in panning, but the richest spot is where the most and the heaviest gold has been deposited, on bars. Fig. 55 shows the spots along such a stream where the gold will best accumulate. Bars are always the first point attacked by the prospector in a new country. They are often very rich, but are quickly worked out, and in general do not call for more approved appliances than the cradle or the long-tom.

Example: In Alaska, river bars were worked as early as 1861, near the mouth of the Stikine river. Subsequently gold was found in the bars of many of the other Alaskan rivers. In 1885, bars on the Stewart and Lewes rivers were worked, and soon afterward on Forty Mile creek. Not until 1887 did the pioneers advance from bar mining to gulch diggings, in one of the branches of Forty Mile creek. Since that time the practical exhaustion of the bars has thrown all the enterprise into gulch mining, and even into bench mining.*

BEACH PLACERS.

What are beach placers?

When a river, rising in a gold-bearing region, reaches the sea with a slow current, it carries only fine mud or silt, and the finest possible particles of gold. These gold flakes almost float on the water; they are largely taken into solution by the sea water, whence it comes that this water

* H. B. Goodrich, 18th Annual Report United States Geological Survey, Part III, pp. 107-125.

contains gold to the amount of about 11 milligrams to the ton.* Part is probably deposited with the settling mud, but the amount is very small and of no direct commercial importance.

But where the rivers discharge into the ocean with a strong current, they carry coarse rock fragments and gold particles of considerable size, which are deposited on the sea shore. The waves and currents work this material sidewise till it forms beaches extending along the coast. The surf, continually moving that portion of the material which comes within its reach, often effects a concentration, the gold being accumulated and much of the lighter material swept away. Shore ice, especially in northern regions, may also be sometimes an important agency in working over the material. Thus beach placers are formed.

Sometimes the shore waves undercut a gravel bank containing gold, and then concentrate the material in the same way as before. This kind of beach placer differs from that above mentioned, in that the rivers do not directly contribute the gold to the beach; yet they do it indirectly, for the gravels undercut by the waves have generally been brought to this position by rivers—that is, they are broad valley gravels, or they are old sea-shore gravels brought down by former streams, and raised high and dry by an uplift of the crust.

Example: Among the most famous beach placers are those of Nome, Alaska, which caused a stampede of many

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* Luther Wagoner, *Transactions* American Institute Mining Engineers, Vol. XXXI, p. 807.

thousand prospectors in 1900. These are examples of the type of beach placers described in the last paragraph. In this region the rocky hills are bordered along the sea by a flat coastal plain, composed of auriferous gravels brought down by rivers and spread out under the sea as a marine shore deposit, at a time when the land was at a lower level than at present (Fig. 56). Subsequently the land was uplifted, and the marine gravels became transformed into the present shore plain. The strong waves of this region cut back the gravel and wash it away, and concentrate the gold, forming rich, but limited deposits. Therefore the gold in these placers has been successively concentrated by waters more than once.

Fig. 56. Diagrammatic section of beach placers at Nome, Alaska. After Schrader and Brooks.*

Do beach placers extend seaward under the water?

Beach placers, like bar placers, are almost invariably, from their nature, shallow and hence short-lived. They are confined to a narrow strip along the beach, for, even when the gold has been derived from auriferous gravels forming the shore, these older gravels will be relatively much poorer, and either will not pay for working at all, or must be worked on a larger scale at a much smaller profit per ton. That portion of the gravel seaward from the surf-beaten

* United States Geological Survey, 'Reconnaissance in Nome Region, 1901.'

zone will not have undergone the concentrating action of the surf, and will also ordinarily contain a very much smaller proportion of gold.

BENCH PLACERS.

What are bench placers or bench diggings?

A river valley often shows along its sides shelves, terraces, or benches, part of the old river bottom when the stream was at a higher level, in which bottom it has cut itself a newer and deeper channel (Fig. 57). If the rock region is gold-bearing, and especially if there is gold on the bars and in the valley gravels of the present streams, then gold may be also looked for in the gravels lying on these high benches.

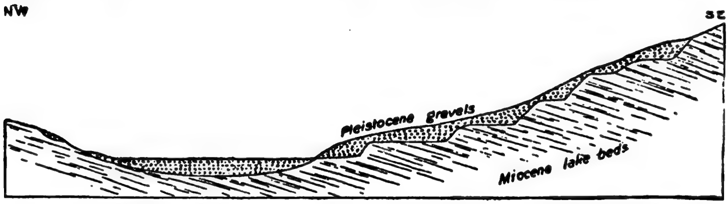

Fig. 57. Bench and valley placers. Section across Rye valley, Blue Mountains, Oregon. After W. Lindgren.

Examples: 1. In the Nome district, Alaska, the sides of the present stream valleys are covered with gravels and marked by terraces or benches, representing former levels of the down-cutting streams. Such benches occur at elevations of from 10 to 100 feet above the present stream. The gravels on them are known to be auriferous.*

2. Rye valley, Blue Mountains, Oregon, is cut in tilted Tertiary lake beds. On its sides is a series of river-cut terraces, on which lie later (Pleistocene) gravels, which are

* Alfred H. Brooks, 'Reconnaissance in Nome Region,' etc., United States Geological Survey, 1901.

gold-bearing (Fig. 57). There are six or eight of these benches, of which the largest is several hundred feet wide. The gravel is coarse and well-rolled. In the bed of the valley are still younger gravels, also gold-bearing. The gold is fine, and is richest at the bottom of the gravel deposits.*

OLD PLACERS.

What are old placers?

Sometimes the earth's surface is disturbed by crustal movement. In some cases the movement may be a general elevation or depression, while in other cases a gentle tilting is produced, so that one portion of a given region is relatively more elevated or depressed than another. Again, the disturbance may be quite irregular, producing a warping of the crust. After such movements the rivers change their velocity and often their direction, adjusting themselves to the new slopes of the surface.

A certain river may be running rapidly down a steeply sloping country, and, on account of its strong current, it is steadily cutting its bed deeper into the rock. A gentle crustal movement occurs, and the lower portion of the river experiences more uplift than the upper. The gradient is changed; the current becomes sluggish; the stream ceases to cut into the rock, and most of the detritus which is brought down is not carried out to sea as formerly, but is smoothed out by the stream along the valley. Thus the valley becomes more and more deeply covered with

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* W. Lindgren, 22d Annual Report United States Geological Survey, Part II, p. 788.

gravels, and hence more and more shallow, and it may end by being entirely filled up.

On the other hand, take a region of sluggish streams which have filled up their valleys with gravels, and think of the region being slightly tilted so that the streams begin to run rapidly. If the tilt is in the direction of the old streams, the new ones will have much of the former direction, but, if it is in other directions, the new rivers may flow at right angles to the old, or even in the opposite direction, for a country whose rivers have filled up their valleys will be nearly flat and will permit the streams to change their beds

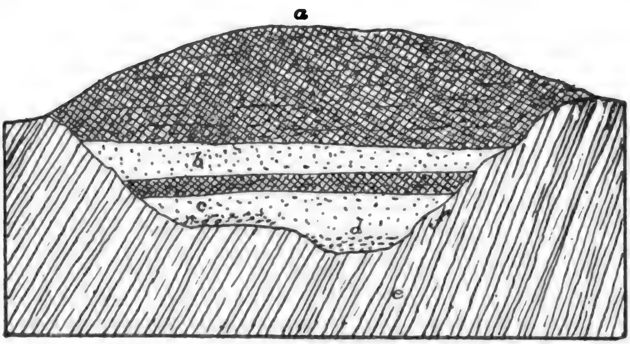

Fig. 58. Generalized section of an old placer, with technical terms as used in California. *a*, volcanic cap; *b*, upper lead; *c*, bench gravel; *d*, channel gravel; *e*, bed-rock; *f*, rim. Adapted from R. E. Browne.*

easily. In any case, new channels are cut. When this is accomplished, the old river gravels will be left between the new valleys, and, in proportion as the latter are deeply cut, the former becomes relatively high above them. These old gravels may have been placers, and, when thus

* Report California State Mineralogist, 1890, p. 437.

left on or under the hills above the present valleys, they may be called old placers (Fig. 58).

Examples: 1. The auriferous gravels of the Sierra Nevada, in California, are classic examples of old placer gravels. They represent Tertiary streams which had entirely different valleys from those of the present day. These old gravels have been sufficiently explored, by drift mining and in other ways, to show in general how the Tertiary valleys lay and in what directions the streams ran; moreover, the general surface of the Tertiary land, between the valleys, can be ascertained. The accompanying map by W. Lindgren* (Fig. 59) shows the topography of this period, with the present topography beneath in fainter lines. From this map it may be seen that while the features of the Tertiary (Neocene) topography showed prominent relief, the surface was much less cut by deep ravines than at present. In general the present streams run at right angles to the former ones.

After the old auriferous gravels were laid down, great flows of volcanic rock filled up the valleys, and, as the tilting took place at about the same time, the new streams followed entirely independent sources. They have now cut down their beds so as to expose the Tertiary gravels at many points.

2. In the Otago gold district, New Zealand, described by T. A. Rickard†, the rivers flow rapidly, and in large part run through narrow gorges which they have recently cut. They have excavated their courses down below the level of their ancient valleys, which were mostly broad and filled

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* 17th Annual Report United States Geological Survey, Part II, Pl. II.

† *Transactions* American Institute Mining Engineers, Vol. XXI, p. 411.

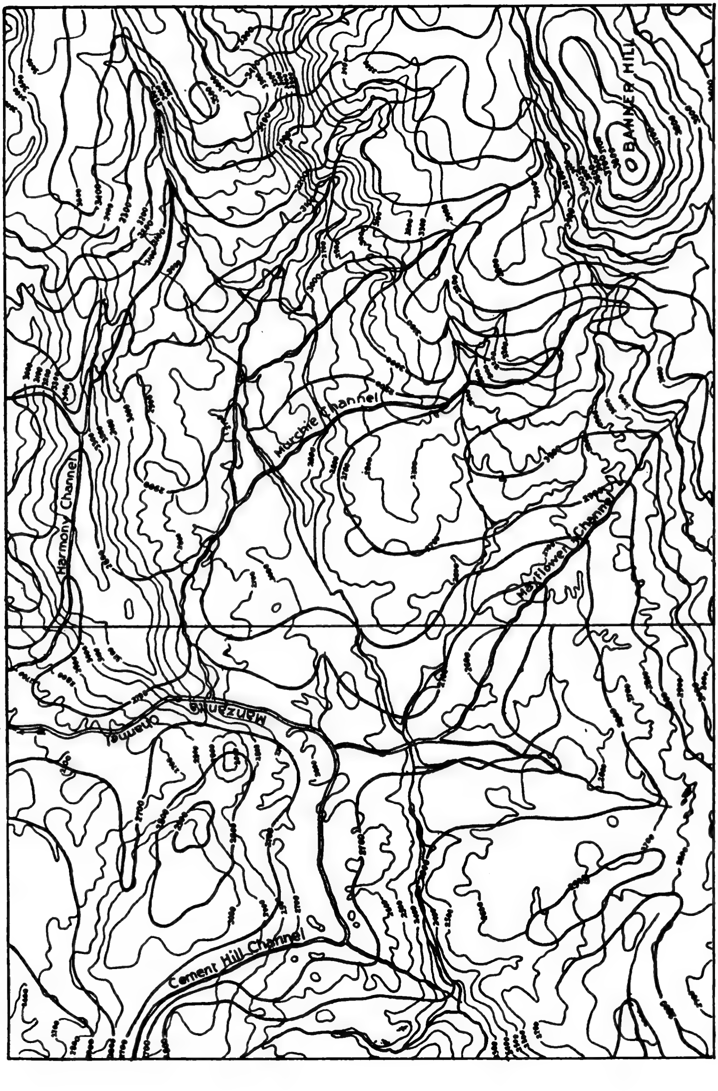

Fig. 59. Contour map of the Neocene bed-rock surface, in the vicinity of Nevada City and Grass Valley, California. Neocene contours in heavy lines; drainage in double lines. Present contours indicated by light lines.

with alluvium. The gravel in these old valleys (of lower Miocene and Eocene age) forms the placer diggings of the present day (Fig. 60).

Old placers, being generally old broad valley placers, are commonly very thick, and contain the most gold in the lower part, the main pay-streak being as a rule just above

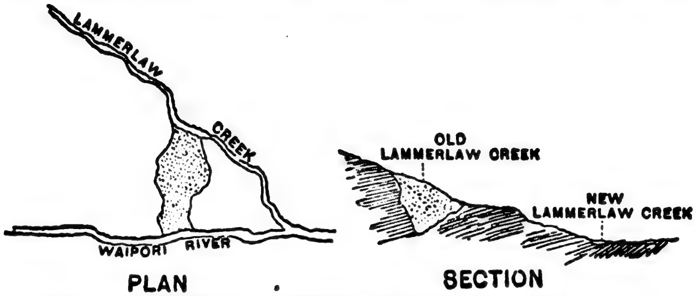

Fig. 60. Old auriferous gravels (Miocene), Otago district, New Zealand. After T. A. Rickard.

bed-rock. On account of their position, they are well adapted for hydraulic mining, and on account of their usually easy drainage by tunnels, for drift mining.

FOSSIL PLACERS.

What is meant by the term fossil placers?

The old placers proper are usually of Tertiary age; they are plainly river deposits belonging to an age just preceding the present, and, save for thin lava beds or barren gravel deposits, they are not covered by younger beds. But placer gravels may be of any age. They may be hardened into rocks (conglomerates), and be folded and faulted so as to lose all evidence of their original relation to any stream.

They may be deeply buried by the accumulation of later beds; and, when again exposed by erosion, they may outcrop either in the mountains or in the valleys. But they will often still retain the gold that was in them originally, and may be profitable for mining; or, when they are attacked by erosion, the gold will accumulate in stream bottoms to form a new generation of placers.

The number of instances where fossil placers permit of productive mining is not so large as might be expected; but it is probable that, in many cases not yet recognized, modern placers derive their gold from old conglomerates which are of this nature. Solid rocks must contain many times more gold than loose gravels to be equally profitable.

Example: On Pole creek, a branch of Cherry creek, Madison county, Montana, a thick conglomerate (maximum thickness 500 feet) lies unconformably below Cambrian beds, and above Archæan gneisses and schists. This conglomerate seems to be auriferous throughout its extent, and the gold in it has been explained as the result of mechanical concentration on the shores of the pre-Cambrian ocean. It is thus a fossil beach placer of pre-Cambrian age.*

RE-CONCENTRATED PLACERS.†

Any one of the classes of placers above mentioned may have derived its material wholly or partly from older placers. Thus the gold may have to pass through several

* A. N. Winchell, *Transactions* American Institute Mining Engineers, Feb.-May, 1902.

† This term was first used by Alfred H. Brooks. 'Reconnaissance in the Cape Nome Region,' Alaska, United States Geological Survey, 1901, p. 149.

successive concentrations, at different times, before it can render a placer profitable. A gulch placer may represent the re-concentrated remains of a bench placer, and a bar placer may be a re-concentration of the gulch placer. Similarly a fossil placer may be attacked by erosion and its gold concentrated anew. Numerous other combinations have commonly occurred.

Example: On the river Galliko, in Macedonia, in the district of Kilkitch, are placers worked at least as early as the time of Philip of Macedon, the father of Alexander the Great. According to modern ideas, they are very low grade, and are washed only by a few peasants. The original source of the gold is in veins which contain silver-bearing galena, carrying small quantities (usually only traces) of gold. These veins have been extensively eroded, the silver and lead have been dissolved and carried away, and the gold has been left in fine particles in the gravels.

During the late Tertiary period a great thickness of such gravels accumulated in the broad valleys of the Tertiary rivers. Although the gold in these gravels is very scarce it is nevertheless everywhere present, and the deposits may be considered as broad valley placers.

In these old gravels certain definite ancient stream beds, usually marked by coarser gravel, can be distinguished, and in such channels the gold is much more abundant than elsewhere. These are probably accumulated bar or stream placers formed in streams which ran through the broad valley deposits, and derived their gold from them. This is the second stage in the concentration.

Since the formation of the gravels the land has been slightly uplifted, and streams have cut down through them. The placers worked to-day are the sands in the present

stream-beds. A small part of the gold in these placers is derived directly from the veins, but most of it comes from the older gravels. Where the stream cuts one of the above-mentioned ancient stream channels, the deposit is relatively rich. This is the third stage of concentration, and only at this point is the gold sufficient in quality to be worked.

PLACERS OTHER THAN GOLD PLACERS.

What are the characteristics of platinum placers?

The geology of platinum placers is like that of gold placers. By its resistance to atmospheric agents of decomposition, platinum, like gold, retains its integrity while other minerals are decomposed and dissolved; and by reason of its great weight, it is left behind in streams where lighter material is carried away. Thus a natural concentration is effected. Platinum is often found with gold in placers, a circumstance to be explained by their common resistance to disintegration, and their common great specific gravity.

Example: The platinum placers of the Ural Mountains, in Russia, have been the most productive in the world. Along the Tura river and its tributaries the placer gravels have a width of from 400 feet to half a mile. The gravel varies from 8 to 24 feet in thickness, and is overlain with peat about 4 feet thick. The richest gravels are those directly above the bed-rock, not exceeding 4 feet in thickness. The pebbles are nearly angular, with frequent large boulders, and are entirely due to river action. Gold and platinum occur together in the placers (Fig. 61).

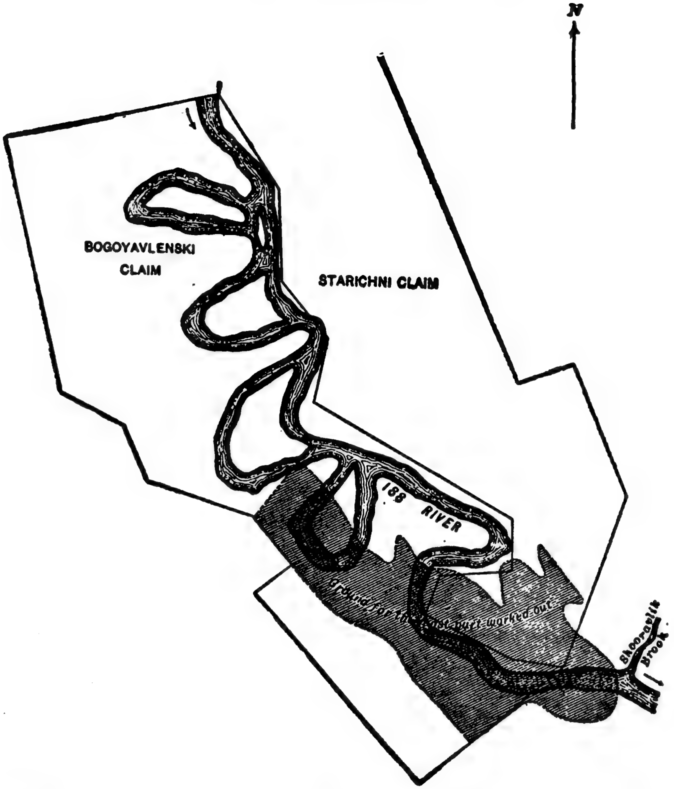

Fig. 61. Platinum placers. Plan of a portion of the river Iss, northern Ural Mountains, Russia. After A. Zaitseff.*

What are the characteristics of tin placers?

A large proportion of the world's supply of tin occurs in placers, usually called stream-works. The metal is in the form of the oxide, cassiterite, a heavy black mineral that does not have a metallic appearance, but has a dull stony

* 'Die Platinlagerstätten am Ural.'

look. It is, however, nearly as heavy as metallic iron, and in gravels tends downward. Besides this, it is with great difficulty attacked by decomposition. Tin placers are made up from the débris of tin-veins in the solid rock, and wherever one of these deposits is found the other may be looked for.

Example: In the district of Siak, Sumatra, alluvial tin, often in workable quantities, is found in the gravels in the

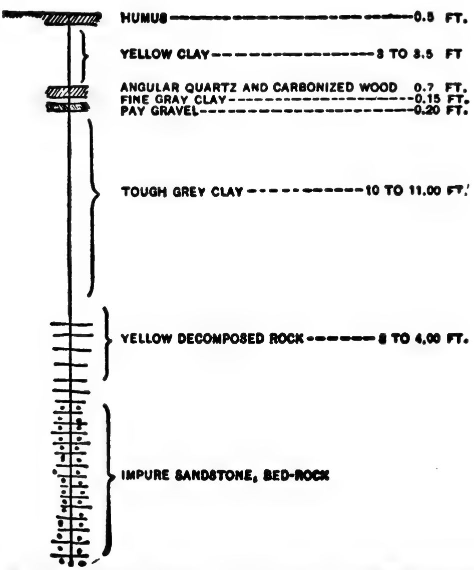

Fig. 62. Section of tin placer, Kotta Ranah, Siak district, Sumatra. After C. M. Rolker.

stream valleys. The bed-rock consists of impure sandstones and quartzites, with some silicious granite containing muscovite and tourmaline—minerals frequently associated with tinstone. The stream channels are covered

by a shallow gravel deposit, growing shallower toward the heads of the streams, till bed-rock is reached. The tin-bearing stratum consists of angular quartz gravel and tinstone. The pay-streak is only a few inches thick, and is overlain by a bed of quartz gravel containing little tinstone; and this by sandy clay and surface vegetable accumulation. It is underlain by a tough gray clay, which, as in the case of gold placers, has formed a false bottom or false bed-rock, by its imperviousness. It is probable that the tin is derived from tin-bearing quartz veins in the underlying sandstone* (Fig. 62).

What is the origin of diamond placers?

In many parts of the world diamonds accumulate in the stream sands and are recovered by washing. The sands are made up of the débris of the diamond-bearing rock. In this case the diamond owes its preservation not to its specific gravity, which is not great, but rather to its hardness and freedom from decomposition, which preserve it when other minerals disintegrate and are washed away.

What other minerals are concentrated in placers?

Among others, monazite, a phosphate of the cerium metals (usually cerium, lanthanum, didymium) which has of late years been sought after for use in the making of mantles of incandescent gas burners, has thus been obtained. In rocks it occurs scattered in small crystals and is not commercially available; but it is capable of being separated from the gravels. In this case the mineral has a consid-

* C. M. Rolker, *Transactions* American Institute Mining Engineers, Vol. XX, pp. 50-84.

erable specific gravity—equal to that of magnetic iron ore—and this operates chiefly in the concentration in the gravels. Like other placer minerals, it is not easily attacked by atmospheric agents of decomposition.

RESIDUAL DEPOSITS

What are residual or rooted deposits?

Residual or rooted deposits form in weathered and softened portions of the solid veins (root deposits). In some countries where erosion has not been very active in sweeping away the surface accumulations, decomposed rock in place extends to a great depth. In this loose surface material the gold, changed to its native state by the atmospheric agents above mentioned, shows a tendency to work downward. The concentration is aided effectually by the winds, which blow away the finer and the looser material and leave the heavier particles. The rain serves the same purpose and removes material both mechanically and in solution. Such deposits are not necessarily in stream valleys, but are found in flat countries or on the side of slopes; the parent or root deposit in the solid rock is never far distant, and may directly underlie the residual deposit. On account of the mechanical and chemical concentration which it has undergone, the residual deposit is very often richer than the vein beneath.

Example: The placers of Kotchkar, in the Ural Mountains, are mostly found immediately under the sod and in intimate relation with the outcrops of the auriferous veins.

Their course does not depend on the surface configuration, but coincides with that of the veins, into which they gradually pass, at a depth of from 20 to 75 feet.*

Are rooted or residual deposits, other than those of gold, known to occur?

Iron ores are sometimes formed in this way, some bodies of phosphate of lime, and other mineral deposits.

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* N. Wyssotzky. 'Les Mines d'Or de Kotchkar,' *Memoires* du comité Geologique, St. Petersburg, Vol. XIII, No. 3, p. 211.

CHAPTER V.

THE STUDY OF CHEMICAL GEOLOGY AS APPLIED TO MINING.

THE STUDY OF ORE-CONCENTRATION.

The study of the chemical laws by which many geologic changes take place is of important economic value. The knowledge of these laws is beginning to throw greater light upon the nature, probable extent and probable value of a given ore-deposit, so that features can frequently be predicted, the foreknowledge of which is of immense value to the miner.

As already explained, the rock-forming elements are constantly in a state of movement and change. The waters which traverse the rocks of the crust are perhaps the most powerful agents accomplishing the change; they are continually dissolving, transporting and re-depositing. In the process of solution they select certain elements in preference to the rest, and in the process of precipitation they concentrate them. Thus, concentrations of most of the elements, to a greater or less degree, are brought about in various places. In the case of the valuable rarer minerals, we call such concentrations ore-bodies.

The important thing, then, is to inquire how these metals migrate and segregate—what is the agency and what are the qualities by virtue of which this is accomplished.

What is the work of mechanical and chemical processes, respectively, in ore-deposition?

The mechanical agencies have been discussed, in the first chapter, in the chapter on stratified rocks, and in the chapter on dynamic geology. They are almost wholly at the earth's surface. Chief of them is water, or rather gravity aided by water; to a very slight extent, wind also. Particles of many kinds of minerals are shaken up and "classified,"* in moving water, flowing downward in streams to the sea under the influence of the earth's gravity; and along sea margins, in waters moved by tides or set in motion by the winds.

The chemical agencies are extremely active by sea and land, on the earth's surface and under it They are very largely responsible, by their disintegrating action, for the breaking up of the surface rock into small pieces, which are sorted over by mechanical agencies so as to form detrital ore-deposits. Moreover, by themselves alone they accomplish the chief work of ore-concentration.

What is the principal agent in the chemical concentration of ores?

Many substances are chemically active in the migration of materials to form concentrations, but the chief vehicle

* This word is used in its technical meaning as regards artificial ore-concentration.

for all these is undoubtedly water. Being dissolved in water, these substances acquire the property of motion and so can exercise their concentrating forces, which otherwise must have been powerless. Outside of solution in water, the chief method by which these substances can acquire the power of motion is by volatilization—changing into the gaseous state, or by passing into solution in gases. Of all the gases which thus play a part, water-vapor or steam, is, again, probably by far the most important.

THE SHALLOW UNDERGROUND WATERS.

What is the source of the ground-water?

Most of the water that falls on the earth as rain or snow sinks into the rocks; the rest is evaporated or flows into lakes or into the ocean. Thus there is a great body of subterranean water.

What is the level of ground-water?

If we sink a well, at first we encounter no water, but at some depth the water oozes into it from every crevice in the soil or rock, and after gathering, it stands at a certain level. This has been called the level of ground-water; it is near the surface in wet regions, and deeper in drier regions. After a rain the water level rises and is often at the surface. When there is little rain it sinks, so that many wells go dry.

The surface of ground-water is not horizontal in a hilly country, but follows in a general way the topographic surface, though it is less accentuated, being further from the surface on hilltops and often practically corresponding

with it in the valleys. Yet a well sunk on the top of a hill will generally find water long before reaching the level of the valley.

Is the ground-water everywhere present in the rocks, and to what depths does it extend?

The distinction of the rock above and below the ground-water surface has been insisted upon by the latest and best writers on ore-deposits. They have even carried the theory so far as to give to the subject an ideal aspect. It has been conceived that below the ground-water level all the openings in the rock, of whatever kind, are saturated with water, whence the phrase "sea of ground-water" has originated, which sea is conceived to extend to a great depth—several miles. But it is possible that this conception is a little too much generalized. In many deep mines, the water is nearly all encountered in the upper levels, and the deeper portions are often dry, even dusty This suggests that the standing body of ground-water does not in general extend to a depth of 10,000 feet, or anything like it, but that its limit is something like 2,000 feet, and in many regions 500 feet.* Some writers are of the opinion that the amount of water which descends into the earth below 2,000 feet is slight, and that it only attains great depths by comparatively large fissures, which are exceptional. Numerous cases of deep, perfectly dry mines, which find water (frequently warm) on tapping some fissure, support these ideas.

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* J. F. Kemp, *Transactions* American Institute Mining Engineers, Vol. XXXI, p. 187, etc.

The penetration of ground-water into rocks is exceedingly irregular. In one place it sinks deeply and freely by means of rock-openings and in another it is almost completely shut out by dense and impervious rocks. It is probable that the universal presence of ground-water is characteristic chiefly of a comparatively shallow surface belt, below which the water which has not been again drawn off at the surface, at a lower level, or has not been used up in hydration processes, is concentrated into the larger fissures.

Example: Prof. Vogt* has written of several deep mines in Norway in which the lowest pump-station is only about 250 meters from the surface. In one of them, the water for use in drilling below that level has to be carried down.

THE WORK OF UNDERGROUND WATERS IN DISSOLVING ROCKS.

How can underground waters dissolve rock-minerals on an extensive scale?

Deep-seated waters are usually ascending, and not infrequently heated. Surface water, in a cold state, is capable of dissolving many materials from the rocks through which it passes Heating the water augments its activity in dissolving materials, and permits it to take into solution a greater quantity of foreign matter; pressure in general has a similar effect. Moreover, some of the materials taken into solution by water, or mechanically held in it in small separate particles, increase its solvent power to a

* *Transactions* American Institute Mining Engineers, Vol. XXXI, p. 165.

great degree. The most important of these substances is probably carbon dioxide (or carbonic acid), which is especially powerful in attacking, and taking into solution, materials but slightly soluble in pure water, such as quartz and many silicates, as well as metallic sulphides. Hydrogen sulphide is also abundant in many ascending waters, as in sulphur springs. By uniting with a little oxygen, the gas changes into sulphuric acid, which transforms many difficultly soluble salts into easily soluble sulphates. Alkaline solutions and especially alkaline sulphides in solution assist the solution of gold and certain metallic sulphides, such as those of silver and copper. Certain substances in solution are especially favorable to the solution of certain other salts. For example, gold is soluble in ferric sulphate, in alkaline iodides, in sodic and potassic chloride,* in sodic carbonate,† sodic sulphide,‡ sodic sulphydrate, etc. Iodine or chlorine in solution unites with certain metals, such as gold, and makes an easily soluble iodide or chloride. From common salt (sodium chloride), in saline waters, hydrochloric acid may be formed by ferric sulphate or sulphuric acid; and manganese oxides, operating upon this hydrochloric acid, would produce free chlorine, which might then act on metals as described above.

In fact, the processes of solution in waters are almost endless and many of them are very complex. The essential thing to understand is that in all waters these processes are

* Egleston, *Transactions* American Institute Mining Engineers, Vol. VIII, p. 455.

† Doelter, 'Chemische Mineralogie,' Leipzig, 1890.

‡ Becker, Monograph United States Geological Survey, Vol. XII, p. 433.

active and thus that all waters are capable of taking most mineral matters into solution; and that deep-seated waters, on account of the generally greater temperature and pressure, as well as on account of the intimate way in which they pass through rocks, and the length of time that they spend in passage, are more powerful solvents than surface waters. Therefore, given metals to dissolve, such as are found in desseminated form in most igneous rocks and in some sedimentary ones, and given waters circulating through these rocks, we may be sure that the underground waters will become charged to a certain extent with the metals, as well as with most of the other mineral substances which they encounter in transit.

Do we know, as a matter of fact, that underground waters do carry mineral matter in solution?

It is not only by theory that we come to this conclusion. In many waters, it is true, the amounts of some of the rarer elements (such, for example, as the precious metals) held in solution, are so small that we are unable to detect them chemically; but in other waters analyses prove their presence. Rain water, having been evaporated, has become purified by a natural process of distillation; but ground-waters always contain small amounts of the elements of the rocks or soils they have traversed. Many waters contain iron, which they deposit as soon as they become exposed to the oxidizing effect of the atmosphere; thus, in many swamps and stagnant pools we find a red deposit of hydrated iron oxide. In limestone regions, the waters contain a considerable amount of lime. Cold

springs may contain many different salts in solution, such as various earthy and alkaline carbonates, sulphates, and chlorides, silica, etc. The hot springs which issue at the surface, or are tapped by mining explorations underground, are still more highly charged with these substances.

What rare mineral elements and metals are found in underground waters?

A familiar example is the natural lithia water, which occurs in springs and contains a considerable quantity of the salts of the element lithium, not abundant in nature. This is used for medicinal purposes. Of more immediate interest to the subject of ore-deposition is the established presence of the salts of arsenic, antimony, zinc, lead, tin, etc., even of gold, in many mineral springs.

Examples: 1. The deep waters from the 2,000 foot level of the Geyser mine, Silver Cliff, Colorado, were found by W. F. Hillebrand to contain silica, alumina, iron, manganese, lime, strontium, magnesium, potassium, sodium and lithium compounds, together with carbonates of lead, copper, and zinc.

2. The springs at Rippoldsau and Kissingen, southwest Germany, have been found to contain tin, antimony, copper and arsenic.*

THE WORK OF UNDERGROUND WATERS IN PRECIPITATING MINERALS.

Are minerals precipitated from solution in concentrated form?

That materials are deposited from underground waters

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* F. Posepny, 'Genesis of Ore-Deposits,' p. 43.

we know from actual experience. These materials include not only the commoner ones, such as calcium, sodium, silica, etc., which are deposited as tufa around the outlets of springs; but also the less common elements. The waters that bear the minerals obtain them slowly, picking them up here, there, and everywhere, but it is not everywhere that the proper conditions occur for precipitation. The result is that where the favorable conditions do occur, a good deal of the materials in question are likely to be precipitated, for an endless supply of water comes, each bringing and contributing its mite. In this way concentration is effected, and from a state of dissemination in the rock, so thinly spread that the most expert chemist detects it with difficulty, lead may be concentrated to form enormous bodies of galena, or gold may be concentrated to form such great nuggets, each worth a fortune, as have been found in Australia. It becomes necessary then for the investigator to gain, so far as he may, some idea of what these conditions are.

Why are ores especially apt to be concentrated along water-courses?

In the first place, it has been pointed out that, other things being equal, ores are most likely to occur along water channels, such as a fracture or set of fractures, a porous bed, etc. This is primarily because in such water-courses an enormous volume of water continually passes, and to a less degree because here the conditions are more favorable to deposition than elsewhere. Into unfractured or otherwise relatively impervious rock, even if the condi-

tions for deposition are of the best, only a small amount of water attains, and consequently not enough metals are ever brought to form an ore-deposit. But, where the conditions favorable for deposition occur along a water-course, then the supplies of materials are so great that eventually a large body of metallic minerals may accumulate.

MANNER OF DEPOSITION IN THE DEEPER UNDERGROUND REGIONS.

In what forms are metals usually deposited in the deeper underground zone?

Most of the metals are deposited in the deeper region (and to a great extent also in the shallow underground region) as sulphides. Under special conditions, other compounds are precipitated, such as carbonates and silicates. The deposition of zinc silicates at Franklin (New Jersey) is an illustration of the latter. Metals may also be precipitated in the native form, as is probably often the case with gold, platinum, copper, etc.; they may form rarer combinations such as arsenides, tellurides, etc., or they may be deposited as oxides.

Under what conditions are metals precipitated as oxides in the deeper underground regions?

We generally think of the formation of oxides as characteristic of the surface, and of the sulphides as the natural products of the deeper regions. This is true, as a rule, for sulphides commonly change into oxides during the pro-

cess of weathering. But the opposite extreme of conditions from those prevalent near the surface, the most intense heat and pressure, and the presence of strong solutions and vapors may, also, produce oxides. An oxide of iron, hematite, is often deposited from gases in volcanoes. Magnetite and hematite are also found in the contact-metamorphic deposits, formed by the highly concentrated, heated, and compressed solutions and vapors given off from cooling masses of molten rock.

Within molten but slowly solidifying rocks, oxides of iron (magnetite and titaniferous magnetite), and probably oxide of iron and chromium (chromite, chrome iron), etc., are accumulated to such an extent as to form ore-bodies. At Franklin Furnace, New Jersey, oxide of zinc (zincite) and oxide of iron, zinc and manganese (franklinite), have been formed under conditions of great depth, heat, and pressure, as indicated by the uncommon minerals with which they are associated—minerals usually found in contact-metamorphic ore-deposits—and by the highly metamorphosed condition of the beds in which they lie.*

Oxides formed under these conditions may be associated with sulphides formed at the same time, as is the case in some contact-metamorphic ore-deposits.

What causes the precipitation of sulphides from solutions?

One of the most important causes is the presence of organic matter, in shales, sandstones or limestones.

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* J. F. Kemp, 'Ore-Deposits of the United States,' p. 257.

How does organic matter cause ore-deposition?

First and, probably, most important, the carbon of the organic matter may unite with the soluble sulphates of the metals, and, by abstracting the oxygen from these salts, cause the formation of sulphides which, being relatively insoluble, are precipitated. The carbon and the oxygen unite to form carbonic acid, which is carried on by the water in solution, and immediately assists in the dissolving power of this water. Second, much organic material contains sulphur, and by decomposition this sulphur may become sulphuretted hydrogen. A rotten egg is a familiar example, emitting the disagreeable peculiar odor of this gas. When this sulphuretted hydrogen comes into contact with soluble salts of the metals it combines with them and precipitates the salts as sulphides. For example, a solution carrying copper and iron chlorides would be precipitated by sulphuretted hydrogen as chalcopyrite, hydrochloric acid being the other result. This acid goes off into the water and aids further solution and concentration.

Most beds containing organic matter give off a certain amount of sulphuretted hydrogen. In fact, certain shales and limestones have this peculiarity so marked that the former are called by the Germans stink-shales (stinkschiefer) and the latter by ourselves, fetid limestones.

What other causes of ore-precipitation are there?

Another important motive for deposition is operative when metallic salts in solution come in contact with rock minerals with which they can combine to form a mineral

compound more stable and less soluble than that already existing. This is in accordance with a fundamental law of chemistry, and the result is the very important process of replacement.

In what manner do replacement deposits form?

The replaced rock is dissolved by the water and for each particle taken up a particle of vein material is deposited in its place. Microscopic study shows how insidiously the solutions can work their way through the apparently solid rock. They circulate along even the tiniest cracks and between the crystals. From there they penetrate into the interior of the individual grains, first following the cleavage planes. The rock undergoing displacement may be sprinkled with disconnected crystals of the ore, the channels by which the ore-bearing solutions have come being invisible. Finally most or all of the rock may be removed, leaving a solid ore-mass.

How can one recognize a replacement deposit?

From the condition of the formation of such a deposit one usually finds all stages from the rock sprinkled with ore-minerals to the solid ore. There is a usual absence of banding, and the ore-bodies are apt to be irregular, with ill defined boundaries. Yet, since they usually follow some water channel, they may have in one or more directions definite extensions, and so may be classified from the standpoint of form, either as disseminations, irregular masses, shoots (pipes or chimneys), or veins.

Sometimes the ore-mineral occurs as a pseudomorph, after one of the original rock minerals—that is, it has the peculiar crystal form of that mineral—which is conclusive proof of replacement. One may also sometimes find fossils completely changed to an ore-mineral or even to a native metal.

Example: The lead-silver deposits of Aspen, Colorado, have formed chiefly from replacement from limestone and dolomite.* Mineralization began along fractures (often microscopic) resulting from some rock movement, and often attendant upon actual faulting. From the fractures the metallic minerals penetrate the adjoining rock. Fossils have been found which are imbedded in the ore, or have been so changed as to form a part of the ore. Fig. 63 shows a mass of pure native silver from Aspen. In this, part of a perfect fossil shell is firmly fixed. At another place a fossil was found completely turned to zinc and lead sulphides and carbonates.

Are replacements always in limestones or dolomites?

Replacement deposits also occur in difficultly soluble rocks, like quartzites and granites. Large ore-deposits in such rocks chiefly due to this process are abundant; and, even in many deposits where the ore has formed in preexisting cavities, large or small, replacement will be found to have been a very important auxiliary process.

Examples: 1. The formation of auriferous quartz veins by replacement of schist along zones of crushing, in the

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* Monograph XXXI, United States Geological Survey, pp. 206-236.

district of Otago, New Zealand, is described by T. A. Rickard.*

The sketch (Fig. 64) covers a width of 5 feet. Instead of forming a narrow clean-cut crack or fissure, the soft schist is traversed by a crushed zone bounded by parallel fractures. The parts between the two lines of fracture form the beginning of the "mullocky reef" of the Australian miner,—that is, a lode carrying a large proportion of included country rock. Percolating waters deposit their

Fig. 63. Fossil imbedded in native silver, Aspen, Colorado. From J. E. Spurr.

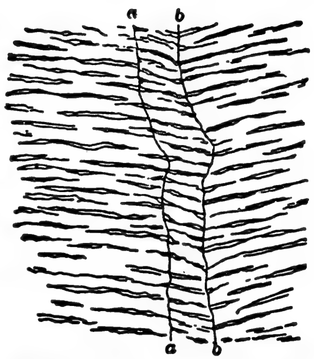

Fig. 64. Type of lode in Otago, New Zealand. The crushed zone between *aa* and *bb* may be entirely replaced. After T. A. Rickard.

quartz first along the lines of parting, and we get a twin system of veins; and, if the action be continued further, the intervening filling is also silicified. It may seem a long step from a lode where the larger part of the gold-bearing material is crushed rock, to a massive vein of clear auriferous quartz, yet the difference is one of degrees only, being due to the variable extent to which the quartz has replaced the rock.

* *Transactions* American Institute Mining Engineers. Vol. XXI, p. 418.

2. The ore-deposits of Monte Cristo, in the Cascade Range, Washington, have formed* chiefly by replacement of the granitic rocks and andesites in which they occur. The mineralizing waters have come into the rocks along joint planes, and have then replaced the wall rock, frequently forming bodies of solid ore (chiefly sulphides, such as iron pyrite, arsenopyrite, blende galena, etc.) several feet in thickness. From the joints the waters make their way into cracks of microscopic dimensions, and so, little by little, attack every part of the rock. Of the original minerals of the granitic rocks (tonalite) and of the andesite (these minerals comprising chiefly quartz, feldspar, hornblende, mica, magnetite and augite) all except the quartz are decomposed, and new quartz, calcite, pyrite and other sulphides grow gradually in their place. With a moderate proportion of sulphides in the altered rock, it becomes an ore, with a quartz and sometimes a calcite gangue.

Does the presence of metallic minerals bring about the precipitation of others?

Metallic oxides and sulphides, already existing in a rock or vein, may act as precipitants of dissolved metallic salts. Sulphides often change their composition in doing so, and form a compound richer in the metallic base than before. Thus chalcopyrite, a mineral containing 34.5 per cent of metallic copper, may be transformed into bornite, containing 55.5 per cent. Iron sulphide (pyrite) may unite with copper solutions to produce chalcopyrite, etc. In auriferous quartz veins the gold is very commonly con-

* J. E. Spurr, 22d Annual Report United States Geological Survey, Part II, pp. 831-33.

tained in the iron pyrite, which in many cases seems to have acted as a precipitant.

Sulphides may also induce the precipitation of other sulphides, particularly of similar sulphides, without, so far as we know, any chemical reaction.

How are ores precipitated by the mingling of solutions?

Since different water currents traverse different rocks, composed of various elements, and are subjected to different conditions of heat, pressure, etc., the mineral solutions contained in each one will rarely be identical with those in another. Whenever two currents meet, therefore, the mingling of the solutions must bring about certain chemical reactions and some materials are likely to be precipitated. Where waters containing free sulphuretted hydrogen meet others containing soluble metallic salts, for example, metallic sulphides will be precipitated. There are a host of other reactions which may take place. This is the chemical explanation for the principle of intersections, defined in Chapter IV.

Example: In the Newman Hill deposits, at Rico, Colorado, as described by J. B. Farish, T. A. Rickard, and F. L. Ransome, the ores commonly occur chiefly on the under side of "blankets," which are impervious beds interstratified in the shaly sandstones of the region. These impervious beds have originated in several different ways, but in every case consist of a decomposed mass through which the ascending mineralizing solutions were unable to pass, and so spread out and deposited the metals. Yet the under side of these blankets is not uniformly mineralized; there

are certain rich shoots, outside of which the ore is poorer or is wanting. The blankets and other beds are cut by lodes or fissure-veins. These veins have their upward termination at the blanket, but extend indefinitely down-

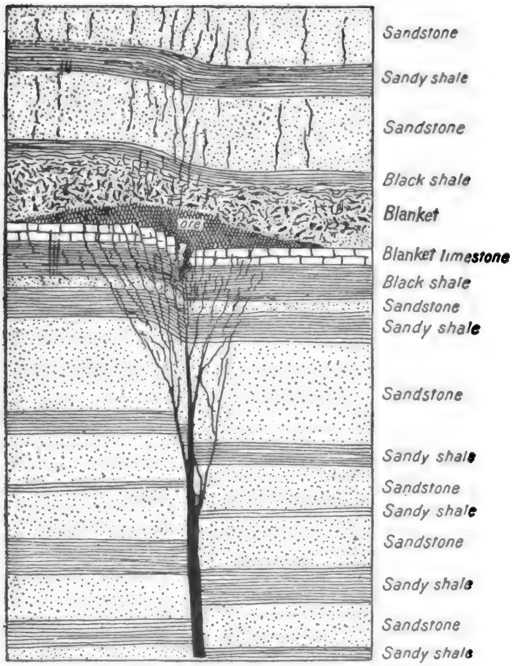

Fig. 65. Diagrammatic section across a lode, and its blanket pay shoot. Newman Hill, Rico, Colorado. Scale, 1 in.=13 ft. After F. L. Ransome.*

ward. The upper end of the veins is capped by a rich deposit of ore, lying in the blanket (Fig. 65). These pay shoots seem to constitute striking examples of ore-bodies at the intersection of circulation channels now occupied by

* 22d Annual Report United States Geological Survey, Part II, p. 291.

the vertical lode and that afforded by a porous zone underneath the blanket. Solutions ascending in the fissures not only found their upward progress barred by the impervious shales, but entered a porous zone traversed by laterally moving solutions, which effected the precipitation of the ores.

Are ores precipitated by decrease of temperature and pressure in ascending waters?

In proportion as underground waters become hotter and under greater pressure, their power of solution increases; therefore when they become cooler and under less pressure, on nearing the surface, their power of solution decreases, and they are obliged to precipitate some of their burden. This statement demands certain qualifications. For example, the laws of solution are different for different materials; and a temperature which is most favorable for the solution of a certain salt may not be so favorable as a lower temperature for the solution of a certain other. But the general principle above stated holds good, and is influential in determining the deposition of ores. Formerly, indeed, it was held to be more important than it is at present, and was called upon to explain most ore-deposition from ascending waters. But now that we recognize the great importance of deposition by mingling of solutions, by contact with organic matter, and by replacement of rocks, or by contact with already precipitated metallic minerals, we see that it must be rather rare that an ore-body is formed by release of temperature and pressure alone. Yet in many cases where we have evidence that some other

cause has been active in ore-deposition, it is probable that this also has been an important factor, without which the precipitation might not have taken place at this point.

For example, a rising column of heated and compressed water may meet with solutions of a different nature at the intersection of another circulation channel; but no precipitation takes place. Further up, where the waters are cooler and under less pressure, they may again meet solution similar to those met below, from another channel, and here abundant precipitation, resulting in the formation of an ore-body, may occur.

Example: The most familiar example of deposition by this cause is in the masses of sinter which are thrown down at the mouths of hot springs, when these emerge into the cool and free open. These deposits consist largely of silica and carbonate of lime; but other substances occur in them in greater or less quantity. Iron, arsenic, tin, and many other metals have been found under such conditions.

At what depth below the surface are ore-deposits formed mainly by ascending waters?

It is probable that some ore-deposits are formed by ascending waters very near or practically at the surface. Such metallic elements as the waters carry in solution, and which they have not precipitated lower down, can hardly fail to be precipitated when coming into surface conditions. The question then is, how deep may these deposits be formed? On that point we have evidence in different mining districts that ore-bodies may be formed at least two or three miles below the surface.

Example: In the Tintic mining district, Utah, there is a series of older sedimentary rocks which in Mezozoic time were lifted above the sea and folded. Soon after this time the ore-bodies were formed. Measurement of the thickness of the stratified rocks found in some parts of the region, but worn away from the ore-bodies now being worked, shows that these ore-bodies were mainly formed at least 12,000 feet below the surface.*

SPECIAL CHEMICAL PROCESSES OF THE SHALLOW UNDERGROUND WATERS.

Are the chemical processes of the shallow underground waters the same as those of the deep underground waters?

The chemical processes of the shallow underground waters (mostly descending from the force of gravity) are usually considerably different from those of the deep underground waters (mostly rising from hydrostatic pressure, heat, contained gas, etc.); but this is not always true. From the mere inspection of the results of the chemical action of a given current of water, it is usually impossible to tell the source or the direction of movement. Sulphides, for example, are deposited equally well by ascending, by descending, and by horizontally moving waters.

What are the peculiar chemical effects of shallow waters?

Waters coming from the surface contain certain gases in solution derived from the atmosphere or the decay of vegetation, which gases are not so abundant in deeper waters.

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*Tower & Smith, 19th Annual Report United States Geological Survey, Part III, p. 715.

Therefore, the chemical effects may also be different. Water coming from the surface contains more oxygen and, as a rule, less sulphuretted hydrogen than do the deeper waters. Surface waters attack the rocks through which they pass, and take much of the material into solution. Silicates, sulphides, etc., are decomposed and, in part, altered to oxides and carbonates. Some of these changes involve an access in bulk, by the addition of the oxygen and carbonic acid from the waters. In some cases this increase is so great as to cause minor foldings in pliable banded rocks, and brecciation in rigid ones. Other chemical changes involve a shrinkage, the amount of material that passes into solution being so large that the net result is to cause the rocks to contract.

Zones of Weathering or Oxidation.

What is the process of weathering?

At the surface, where this contraction is most active, it results in disintegration and crumbling of the rock; further down, in a loss of strength and cohesion, in enlargement of openings, and in the development of cracks (often not actually opened, but only potential), into open fissures.

This general process is called weathering, from being so conspicuous at the surface, where the rocks are exposed to the atmosphere, or weather; and the zone of rocks affected by it (a zone roughly parallel to the surface configuration) is called the weathering zone.

Example: In a tropical country, like Brazil, the surface weathering of rocks is vastly more active than in cooler

climates. Decomposition to a depth of 100 feet is common, and sometimes extends more than 300 feet. The daily range of temperature sometimes amounts to more than 100° Fahrenheit. These changes cause the rocks to crack and to admit moisture and the acids which bring about rock decay. The hot season is the rainy season, and waters falling upon the hot rocks have their temperature raised to about 140°, which makes them more efficacious; and the rainfall is very large. The chief acids which aid in the decomposition are carbonic acid, nitric acid, and especially the organic acids derived from the decay of the abundant plant and animal life.*

Is the weathered zone the same as the zone of oxidation?

This practically corresponds with what is called, especially in consideration of ore-deposits, the zone of oxidation, being that belt where the highly oxygenated surface waters have altered the sulphides more or less thoroughly to oxides, carbonates, etc.

Are chemical processes active in the rearrangement of ores in the zone of oxidation?

They produce very marked results. Rocks near the surface are physically shattered; hence, waters gain access to every portion. The shrinkage resulting from the first chemical reactions of these waters carries on the work. The rock crumbles (unless it is immediately swept away by the streams) into a kind of coarse sand, and the waters have an opportunity to search thoroughly every part of it. Much of its substance is dissolved and re-precipitated or

* J. C. Branner, *Bulletin* Geological Society America, Vol. VII, pp. 255-314.

carried away. When re-precipitated it may still be near the surface, or may be far below. In any case the groupings change. Scattered amounts of the metals may be concentrated by this process.

What is the iron hat (iron cap) or gossan of an ore-body, and how is it formed?

In most ore-bodies iron forms an important part, even when the chief values are in some other metal. Many copper ores, for example, consist wholly or in part of chalcopyrite, the sulphide of iron and copper. During and after the weathering and oxidation of the surface parts of these deposits, the metals other than iron may be leached out, carried down and re-precipitated, leaving the iron (with quartz and other gangue minerals, if they were present in the original deposit), in the form of a soft yellow limonite, or sometimes as hard brown limonite or hematite (oxides of iron). This iron covers the valuable ore, which is found by sinking through it. In Germany it is called the iron hat, in Cornwall gossan, and in America generally iron cap (or capping). A strong iron cap is a favorable sign of a large ore-body beneath.

Example: *At the Cobre copper mines, in the province of Santiago, Cuba, the principal lode and the chief courses of the ore are indicated at the surface by spongy quartz and iron oxide, with highly colored clays. Immediately beneath, or in the clays, were found oxides, sulphides and

* Professor Ansted. Quoted by Hayes, Vaughan, and Spencer, 'Geological Reconnaissance of Cuba,' 1901.

carbonates of copper. Further down, these all change to copper pyrite (sulphide of copper and iron), which may be regarded as the original ore, the carbonates and oxides of copper having been derived from it by oxidation, and the iron cap formed by the leaching of the copper out of the iron and quartz. The oxidized zone extends down nearly a hundred feet.

PRECIPITATION OF ORES AT THE SURFACE.

How are ores precipitated, from solution in surface waters, in swamps?

Water containing iron finds its way into swamps, and on standing there for a while the oxygen of the air combines with the iron carbonate in solution. Carbonic acid is evolved, and hydrated iron oxide; the latter forms a scum on the surface or sinks to the bottom. Successive precipitates may accumulate till a considerable deposit is formed. These "bog-ores," as they are called, have been, and are still, much exploited for commercial purposes. They include not only the ores formed at the present day, but those of past ages. The latter, like coal beds, have been covered by later sediments and so preserved till now, when they are often exposed by erosion.

Example: In the Three Rivers district, Quebec, Canada, extensive deposits of bog iron ore have formed and are now forming. The iron contained in the streams is deposited in swamps, streams, and lakes, wherever the water is for a time stationary, or choked with vegetation. Beginning as a light film, the ore gradually accumulates to thick crusts, and in course of time a very considerable amount accumu-

lates, so that in places it is dug out for commercial use. This iron has been used since 1730.*

Are ores precipitated from the waters of lakes and oceans?

Waters entering oceans, lakes, etc., carry mineral matter which may be finally precipitated on the bottom. In confined lakes or inland seas, important deposits of common salt, gypsum, magnesium and potassium minerals, etc., are formed. In the sea, manganese solutions are precipitated on the bottom in concretionary form, as has been proved by dredging. Much of the commercial manganese has this origin, the manganiferous layers of old sea sediments being attacked by land waters, subsequent to uplift and erosion, and the manganese being thereby more highly concentrated. Other metals, such as copper, and even si ver and gold (chemical analysis has proven the presence of these and many more in common sea water) are probably precipitated in small quantities in the sediments accumulating in the sea bottoms and along the shores; and these slightly metalliferous layers, after uplift, may yield to land waters a material which, after further concentration by them, will form workable ore-bodies.

Example: In the Paleozoic region of Georgia occur ores of manganese, which are found in connection with only three formations—a limestone, a dolomite, and a quartzite. The manganese is in clays residual from the decay of the rocks, and has evidently been concentrated from a disseminated state in these beds or overlying strata now

* Résumé by J. F. Kemp, 'Ore Deposits of the United States,' p. 90.

removed by erosion. It is supposed to have been derived originally from silicates in crystalline rocks, from which it was taken by streams in solution to the sea, where the Paleozoic strata were being deposited, and was precipitated in them. Long afterwards, when these beds were again part of the continent, surface waters dissolved and concentrated the manganese so as to form ores.*

Are mineral deposits ever formed at the surface by the evaporation of underground waters?

A special and peculiar phase of the circulation of water in rocks, and especially in soils close to the surface, is dependent upon the surface evaporation. Where evaporation is strong, the surface would quickly become entirely dry were it not that moisture from deeper down rises to take the place of that removed. This action is particularly strong in hot and arid climates. The mineral content of the evaporated waters is left on the surface, forming the crust of salt or "alkali" familiar in desert regions. In natural hollows or bas'ns in the topography, beneath the surface of which the groundwater accumulates (even though it is not abundant enough to stand long above the surface), so much material is brought to the surface that the incrustation is often of economic value. Such deposits consist chiefly of salt, borax and soda. In some cases it is possible that useful accumulations of certain metals may be formed in this way.

Example: In western Colorado, deposits of uranium

*T. L. Watson, *Transactions* American Institute Mining Engineers, Feb., 1903.

and vanadium occur in Jurassic strata. The chief mineral is a vanadate of uranium and potassium, called carnotite. The ore occurs disseminated through sandstone, as irregular bunchy pockets in this rock, or along the contact of sandstone with shale. The ore bunches have the appearance of being impregnation deposits, formed by solution along planes of easy circulation, frequently bedding planes. The most interesting fact concerning them is their superficial character. They are flat-lying streaks which in some cases disappear into unmineralized sandstone when followed only a few feet underground. In places the ore has formed along crevices plainly due to recent surface movement, showing it to be not only superficial but very recent.

It is supposed that the ore exists in very small amounts in the sandstone and that the surface deposits have been concentrated from this condition; and it seems extremely likely that this concentration has been effected by the strong evaporation of a semi-arid climate, continually removing the moisture from the surface and leaving the dissolved contents behind in the rocks.*

By a similar process of evaporation incrustations may be formed in caverns.

Example: Nitrates are frequently found in cavern earths. A large amount of saltpeter (nitrate of potash) was taken from the Mammoth Cave in Kentucky during the war of 1812, and from caverns in Alabama and Georgia during the Civil War, for the manufacture of gunpowder. Investigation of these deposits points to the conclusion that the nitrates were brought in by water percolating through the soils above the caves and were deposited on the floors.

* F. L. Ransome, *American Journal Science*, Fourth Series, Vol. X, pp. 121-130.

Currents of air, passing in and out of the caverns, removed the water, leaving the salts in the cave earth. The accumulation of salts occurs only in caverns where the inflow of surface water does not exceed in amount the water removed by evaporation. In wet caves the soluble salts are washed onward with the water bearing them, and so are not deposited. Nitrates deposited under overhanging cliffs have the same origin. As to the source of the nitrates, vegetation furnishes continually, during its decay, a small amount of nitric acid.*

Are there other instances of the precipitation of ores from surface waters?

Waters containing phosphoric acid, derived, for example, from the dung of sea fowls, may change limestones or lime marls lying near the surface from lime carbonate into lime phosphate, of great value as a fertilizer. Numerous other examples might be cited. In gold placers there is, as previously noted, certainly some solution and redeposition of the gold by the surface waters, even though gold is comparatively resistant to solution in general.

Are minerals secreted from surface waters by living organisms?

The precipitation of lime and silica from solution in sea water by incorporation into the shells of marine animals is of vast importance. By the accumulation of such shells on the sea or lake bottoms originate the majority of limestone deposits. A tiny fresh water organism that makes its shell out of iron has been discovered, and the accumu-

* W. H. Hess, *Journal of Geology*, Vol. VIII, p. 129.

lation of these has been held to be important in forming some iron-ore deposits.

Are ores precipitated from surface waters by organic matter?

Precipitation by organic matter plays an important part at the surface, as well as underground.

In the sea, in a certain broad zone somewhat remote from shore and yet not in the greatest depths, the precipitation of silicate of iron (glauconite), is accomplished largely through the agency of organic matter, and through the accumulation of this glauconite, and its subsequent alteration and re-concentration, iron ore-deposits have been formed.

Example: In eastern Texas are found beds of limonite (hydrous oxide of iron) associated with marine glauconitic sands. The silicate of iron was formed beneath the sea, probably chiefly through the agency of tiny organisms, which precipitated the iron and silica, either from fine mud washed out from the land, or from the solution in the sea water, or both. After deposition the beds were lifted up and became dry; then the surface waters decomposed the glauconite. The iron was changed to oxide, and on further concentration (by the surface waters) formed limonite beds.*

Metallic gold, in placer regions, is frequently found in grass roots, having been precipitated there by the reducing action of organic matter. Pieces of wood, etc., in placers, have the same effect.

* R. A. F. Penrose, Jr.. First Annual Report Texas Geological Survey.

Example: On one of the tributary streams of the Galliko river in Macedonia, exceedingly little gold can be got from the gravels, and what is obtained is very fine, but, in some localities, if the grass and turf over which the water occasionally flows be pounded up and washed in a gold-pan, a much larger quantity of coarser gold is obtained.*

Precipitation of Ores in the Shallow Underground Zone.

Turning away from the precipitation of ores at the very surface, let us look at the facts of their precipitation in rocks near the surface. It has already been explained that in the process of weathering the superficial portions of the rocks are largely taken into solution, as well as much of the rock lying within a moderate distance from the surface.

Concentration According to Relative Solubilities.

How do the different solubilities of metallic minerals bring about their selective concentration?

Some materials are more soluble than others, hence some valuable metals, for example, are taken with difficulty into solut on, and, when in solution, are not carried far before being precipitated. Others are more easily soluble and are carried further. The result is that in ore-deposits which have been greatly affected by weathering and the accompanying action of surface waters concentration of metals according to their relative solubilities is very great.

* Observations by the writer.

In the case of a mineral not easily soluble how may concentration take place?

The concentration may take place by the removal in solution of the more easily soluble minerals with which it was originally associated. This forms residual deposits, which are often important. For example, phosphatic lime nodules in limestones are frequently concentrated at or near the surface by the removal in solution of the more easily soluble carbonate of lime in which they were embedded; and often only this surface portion can be worked, the unaltered portions containing too small an amount of phosphate. Iron carbonate or limonite nodules in limestone are concentrated by the same process into workable iron ore at the surface. Outcrops and weathered portions of gold-bearing veins are often richer than the unoxidized portions below, for much of the rock has been removed in solution, while the gold has been attacked to a less extent; hence the percentage of gold in the weathered and oxidized rock is greater than in the unaltered portions.

Example: In the gold belt of the Blue Mountains, in eastern Oregon, the gold-quartz veins, which carry free gold, are more or less oxidized to a depth of from 100 to 300 feet, and this zone is generally richer than the unaltered ore below. At one mine (the Sanger, on Eagle creek,) the uppermost 100 feet showed a narrow vein yielding $25 per ton, while below the vein widened, and the average values were reduced to $12 per ton.*

* W. Lindgren, 22d Annual Report United States Geological Survey, Part II, p. 611.

Are minerals taken into solution re-precipitated in concentrated form?

Concentration by solution and re-precipitation is a common process. In places where there is only one mineral of importance this mineral may be compactly precipitated in the zone of surface waters. Great iron ore-deposits have been made in this way; and concentrations of the more valuable metals are frequent.

Example: 1. In the Tintic district, Utah* (described by Tower and Smith), there is a good example of the enrichment of ores in the oxidized zone. The ores contained in the sedimentary rocks in this district (mostly limestones) are completely oxidized to a depth of several hundred feet, and partially to the lowest points reached in the mine workings. Surface waters have decomposed the original sulphides. The metals thus attacked have been largely taken into solution and re-deposited as new minerals. The metallic minerals of the original deposit are sulphides and sulpharsenides, principally pyrite, galena, enargite and silver sulphide. These have been changed to oxide of iron, sulphate and carbonate of lead, hydrous arsenates, and arsenites of copper, oxides of copper, native copper, chloride of silver and native silver. During these processes the various metals have largely been segregated, and form distinct deposits, so that there are great bodies of ore containing principally lead, or copper, or silver.

In the veins in the igneous rocks, in the same district, the oxide ores carry about twice as much silver and lead as the sulphide ores, there being nearly a corresponding decrease in iron and silica. These segregations of the

* 19th Annual Report United States Geological Survey, Part III.

metals result from differences in the solubilities and stabilities of the various minerals.

2. In the Red Cliff mining district, Colorado, the ores occur at two distinct horizons. The first horizon is in Lower Carboniferous limestone, beneath an intrusive sheet of rhyolitic rock, and the ores are replacements of the limestone by iron pyrite and silver-bearing galena on an immense scale. The oxidation of these sulphides to sulphates and oxides may be well observed. The second horizon is from 200 to 300 feet lower, geologically, on the top of a white Cambrian quartzite. The ores are smaller in volume and more irregular in distribution, but are very much richer. They are fine ochreous material, largely basic iron sulphate, containing silver and gold. There is good ground for assuming that these metals have, in part at least, been leached from the ore-bodies of the higher horizon, by solutions of iron sulphate.*

When a number of different metals are thus worked over does a definite arrangement result?

Where a number of metals are attacked by surface waters, the result of their differences in solubility is the formation of rough mineral belts. These follow the surface in general, and each is characterized by a preponderance of certain metals or minerals. For example, in deposits containing lead, zinc, and copper, the effect of descending waters may be to separate the metals into zones, the lead (galena) being above, and zinc (blende) below. Frequently there is a third and still lower one characterized by

*Franklin Guiterman. *Proceedings* Colorado Scientific Society, Vol. III, 1890. Supplement; S. F. Emmons, 'Geological Excursion to the Rocky Mountains,' p. 417.

copper; and a fourth, characterized by iron, has been observed. There are irregularities in these zones, and the different minerals commonly occur together, even in the same hand-specimen; but in a broad way they are often well defined.

SECONDARY SULPHIDE ENRICHMENT.

What is the meaning of the term secondary sulphide enrichment?

The working over and re-concentration of an earlier ore-body into richer sulphides by descending waters has been called secondary sulphide enrichment.

What is the secondary sulphide zone?

In many regions secondary sulphides occur in a more or less definite zone, underlying the oxidized zone and overlying the primary ores (generally also sulphides). The metals are leached out of the oxidized ores by descending waters and carried downward to the unoxidized suphides, where they are themselves precipitated as sulphides, often by the direct influence of the primary ores. Such secondary sulphides are commonly richer than the primary ones.

In the cases where ores are precipitated as sulphides, from descending waters, where does the sulphur come from?

The decomposition of less stable sulphides is supposed to furnish the necessary sulphur. Even where no large body of older sulphides exists, disseminated sulphide of iron (pyrite) may occur as it does in many sedimentary

and most igneous rocks, even in those apparently fresh. Other possible sources of sulphur are sulphur-bearing waters, and the sulphur frequently present in sedimentary beds containing organic matter. Soluble metallic sulphates in surface waters may sometimes be reduced to sulphides.

May an ore-body be formed wholly by descending waters where none already exists?

In the case where no older deposit exists, ore may still be formed by descending surface waters, provided that the rock through which the waters percolate has a sufficient quantity of disseminated minerals.

Example: The formation of iron ore-deposits by descending waters has taken place in certain parts of central and

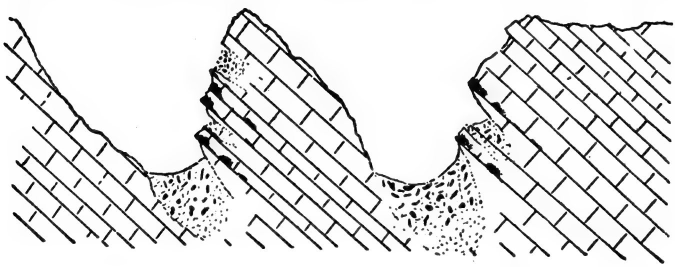

Fig. 66. Deposition of iron ore by descending waters, in the bedding and joint seams of limestone; and nodular iron ores in residual clay in the hollows of the limestone. Section at the Pennsylvania Furnace ore-bank, Pennsylvania. After T. C. Hopkins.

eastern Pennsylvania. The ores are oxides, largely limonite. They occur as rounded or elongated fragments, with residual clay, in irregular deposits in cavities which extend from the surface down into beds of limestone, clay or sandstone (Fig. 66). The original source of the iron is in Paleo-

zoic shales and limestones, where it is disseminated in the form of carbonate, with some sulphide and silicate. The segregation of the diffused iron into the ore lumps is brought about by descending surface waters. The metal has been dissolved by the organic and carbonic acids of these waters, and precipitated in concentrated form, in its present position, in part as oxide, and in part as carbonate, which has subsequently been oxidized. Weathering of the rock leaves the ores embedded in residual clays.*

Are ore-bodies formed entirely by descending waters likely to be so important as are secondary sulphide enrichments?

Except in the case of iron and some other of the commoner ores, such ore-masses are usually smaller and leaner than those formed by secondary enrichments. Moreover, at a moderate depth below the surface the mineralization is apt to fail to such an extent as to make the deposit unworkable. This depth varies with the character of the rock. Where the rock openings are small and closely set together, the belt of mineralization will follow more closely the surface and will often extend only a distance of several hundred feet; strong fracture zones or fissures, however, may carry the surface waters and their effects locally much deeper.

Features of the Process of Re-concentration of Pre-existing Ores by Shallow Descending Waters.

Are the ores concentrated by shallow descending waters all leached from the present oxidized zone?

Whether or not the concentration by descending waters

* T. C. Hopkins, *Bulletin* Geological Society of America, Vol. XI, pp. 475-502.

acts upon the previous ore-body, the results are not simply those which can be obtained from a given belt of oxidized rock at a given period. In most places thousands of feet of rocks—often several miles—have been removed by erosion to lay bare the present surface. As the surface rocks are stripped away, they may contribute a part of their metallic contents to the rocks below, and so the surface zones of mineralization continually migrate downward, keeping pace with the erosion. The result is that we may have, below the oxidized zone, not alone the concentrated metals of that zone, but contributions from many ancient oxidized zones, long since swept away.

Are regions with the deepest zones of weathering or oxidation most likely to be attended by rich concentrations by descending waters?

This consideration leads to the comparison of oxidized zones and zones of metal concentration by surface waters. Oxidation is a slow process. Hence, in countries of little erosion (which are necessarily those of little moisture) oxidation has plenty of time, and extends, partially at least, to great depths, in spite of the fact that atmospheric waters are the chief agents of oxidation. In countries of great rainfall and erosion, the zones of oxidation, though rapidly formed, may be swept away as rapidly, so that it hardly penetrates below the surface. Yet in the latter case the zone of concentrated ores may be more rich than where the oxidized zone attains unusual development, for the thickness of rock removed in a given time by erosion is many

times more than in the arid region, and therefore larger quantities of metals are brought into solution and made susceptible of re-precipitation and concentration.

What are the conditions determining the concentration of ores by descending waters in the surface zones?

In different cases the concentration of pre-existing veins by surface waters varies, whether the newly-formed minerals take the form of oxides, chlorides, carbonates, or sulphides.

The conditions which determine this variability of effect are divisible into three classes.

1. Relative quantity of solutions and slope of land surface.
2. Chemical and physical nature of ores.
3. Chemical nature of solutions.

How does the relative amount of rain- and snowfall, and the surface slopes, affect this process?

The factor determining the relative quantity of solutions is climate. On this depends the amount of moisture precipitated. Other things being equal, a large quantity of water will do more work in dissolving and re-precipitating mineral matter than a small quantity.

Another important circumstance is the relative rapidity with which that portion of the waters which remains on the surface wears away the rocks. This condition is dependent, with a given quantity of rainfall, upon the surface slopes.

We may consider the chances in four different kinds of country:

Moderate to well-watered country with steep slopes.

Moderate to well-watered country with slight slopes.

Arid country with steep slopes.

Arid country with slight slopes.

What are the chances for this process in a well-watered country with steep slopes?

In a well-watered country, the level of ground water will be high, and, as this corresponds in general to the upper level of sulphides, the zone of oxidation will be relatively shallow. If the slopes are steep, the surface will wear rapidly, so that the oxidized zone may even be removed as fast as it forms, and the sulphide zone may almost or quite come to the surface.

In this case the abundance of waters will tend toward a complete rearrangement of metals in the superficial zone, but the rapid wearing away is apt to interfere with this process, and the concentrated metals which outcrop at the surface are largely removed and lost.

What is the usual effect of descending surface waters in a well-watered country with slight slopes?

If the slopes are slight, and the supply of water abundant, the oxidized zone will be well marked and thoroughly altered, though relatively shallow. The rearrangement of metals according to their relative solubilities will be comparatively complete. Under such conditions, gossan, or iron capping, is common. According to the solubility of the

minerals and metals in the orginal deposit, the gossan may be exceptionally rich; or very poor, with rich ores below, in the enriched oxidized ores and in the enriched secondary sulphide zone.

What are the characteristic effects of descending surface waters in an arid region with steep slopes?

In an arid region, where the supply of water is small, the changes wrought are characteristically incomplete. In the zone of surface alteration oxidized and unoxidized ores occur side by side, both often occurring together at or near the outcrop. Therefore the oxidized zone, and the zone of secondary sulphide enrichment, are not so well defined as in regions of heavier rainfall.

The level of ground water being low or wanting, the zone of partial oxidation extends far down. For the same reason, the secondary sulphide zone is apt to be indistinct, and sometimes, perhaps, not separable from the oxidized zone.

In sum, the degree of rearrangement is not likely to be so complete as in a well-watered region, but the enriched zone is likely to be as thick or thicker, and will be more of the oxidized than of the secondary sulphide nature.

Where the slopes are steep, the occasional rainfalls or snow meltings have great power to strip the surface, and carry it down to the valleys; and if this stripping is not so active as in a well-watered country, the same scarcity of water limits the rapidity of ore-concentration in the surface zone. Here, then, the zone of surface rearrangement is apt

to be relatively not so thick, and at the same time is incomplete.

In an arid region with slight slopes what are the effects of descending surface waters?

Where the slopes are slight, in an arid country, the wearing away will not keep pace with the alteration in the surface zone. Hence, in the course of time, the rearrangement of minerals will extend to a very considerable depth.

What are the most favorable conditions for oxide or sulphide concentration near the surface?

It seems that great precipitation is more favorable to this result than aridity, and the slight slopes to steep ones. Most favorable is the combination of slight slopes and abundant precipitation; the combinations of abundant precipitation and steep slopes, and of slight precipitation and slight slopes, are perhaps equally favorable one to another; but in the first case the oxidized zone will be slight, and the secondary sulphide zone important, and in the second the reverse will be true.

How does the chemical and physical nature of veins affect their superficial concentration by descending surface waters?

The rearrangement depends upon the facility with which the ores are taken into solution and re-deposited, and so easily soluble ores should be more quickly and completely rearranged than minerals which are difficultly soluble.

Quartz veins, for example, containing free gold, (which is relatively difficultly soluble), should not be expected to show so much rearrangement as copper ores, which are relatively easily soluble.

The physical conditions of the veins also largely govern this action in the surface zones. If the metals are, from the nature of the vein, easily accessible to surface waters, the result will be more complete than if they are not readily attacked. This may depend on the original characters of the vein, or on subsequent conditions. For example, veins consisting largely of metallic minerals are much more quickly attacked than those where the metallic minerals are small in amount and locked in gangue, such as quartz. Also veins that have been shattered or fractured since their formation are easier of attack than those which are unbroken. The actual outcrop of a vein is almost always shattered by changes in temperature, so that this is a specially favorable field for alteration by surface waters.

How does the character of the solvents contained in descending surface waters affect the nature of ore-concentration by them, and what determines their character?

The character of the solvents is often as important as the relative solubility of the metallic minerals. In one region where a given solvent is present, a given metal, easily attacked by it, may be readily dissolved and re-deposited; in another case the same metal, for the lack of such solvent, may remain comparatively little altered. In descending

surface waters the character of the contained solvents may depend on the nature of the ores in the vein, on the nature of the gangue, of the wall-rock, of the soil, or of surface deposits of various kinds. Through all of these descending waters must pass.

EXAMPLES OF SECONDARY ALTERATION BY SURFACE WATERS.

1. Gold quartz veins in a country of steep slopes and abundant precipitation. Gold belt of the Blue Mountains of eastern Oregon.*

Typical gold-quartz veins (that is, quartz veins containing gold, which is generally associated with iron pyrite scattered through, and embedded in, the quartz) are, it seems, not always easily affected by surface waters. In the first place the great mass of quartz protects, to a large extent, the relatively small quantity of pyrite from the air and surface waters.

In a moist country, where oxygen and carbonic acid are the chief reagents contained in the waters which sink below the surface, gold is little affected. The waters oxidize the pyrite, and the dissolved iron is carried off. Ferric sulphate, which may be one of the products of the oxidation of the pyrite, can dissolve gold; but either this action is slight, or the gold is almost immediately precipitated again, for experience shows that the bulk of the gold stays in the free state in the oxidized outcrops.

It even remains there, where erosion is very weak, after the outcrop has crumbled to soil, and forms residual placer

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* Waldemar Lindgren, 22d Annual Report United States Geological Survey, Part II, p. 611, etc.

deposits (rooted deposits). Frequently such deposits are rich.

Where the slopes are steep and the rainfall abundant, as in the Blue Mountains of Oregon, the surface débris is swept away too soon to permit any accumulation of the kind above mentioned. The water level is high in this region, and oxidation extends down from 100 to 300 feet, and is then only partial. The partially oxidized surface zones sometimes show twice as much gold per ton as the unaltered lower portions; in other cases there is very little difference. An increase of gold and a decrease of silver in the oxidized zone was noted in one case. This is to be explained by the leaching out of a portion of silver by oxidizing waters. Under ordinary conditions silver is more easily soluble than gold.

There is no observable zone of enriched secondary sulphides in this instance.

2. Veins carrying lead, zinc, copper and iron, with gold and silver, with a relatively small amount of gangue, in a region of great precipitation and very steep slopes. District of Monte Cristo, Cascade Range, Washington.

This district has been described by the writer;* and the suggestion made that the ore-deposits as a whole may have been formed by downward moving solutions. But as the waters would have had the same effect upon a body of earlier ore, formed in some other way, the case still serves to illustrate the action of descending surface waters under these conditions.

The climatic and surface conditions are practically the same as those in the Blue Mountains of Oregon, already cited. But while, in the Blue Mountains, concentration in the partially oxidized gold quartz vein is slight, and a zone

* 22d Annual Report United States Geological Survey, Part II.

of sulphides formed by descending waters is not recognized as existing, in the Monte Cristo ores the sulphides deposited by descending waters form remarkably strong and complete zones. The difference is plainly due to the different characters of the minerals involved.

In the Monte Cristo district, as in the Blue Mountains, there is no zone of complete oxidation. Sulphides outcrop at the surface. The zone of even tolerably complete oxidation does not extend more than a depth of ten feet anywhere, and generally is lacking.

Enormously abundant surface waters, keeping the ground-water level close to the surface most of the year, have dissolved the lead, zinc, copper, iron, silver, gold, etc., from their original positions, carried them down, and re-precipitated them as sulphides. The minerals are precipitated roughly in the order of their relative solubility, the least soluble being carried the least distance. Thus the upper zone is characterized by lead (galena), gold and silver, and the lower limit of galena follows the contour of the surface, some 100 to 150 feet below it (Fig. 67). Below this there are some less regular, but still definite, zones characterized successively by zinc (blende), copper (chalcopyrite), and iron and arsenic (arsenopyrite and pyrite). The sulphides near the surface carry an average of 0.95 ounces gold and 12 ounces silver to the ton; at some distance (a few hundred feet) from the surface, the pyrite and arsenopyrite contain an average of 0.6 ounces gold and 7 ounces silver.

A maximum of 600 feet is assigned for the vertical distance between the surface and the bottom of the copper zone.

3. Copper pyrite ores (or iron pyrite carrying some copper) in a well-watered country with moderate slopes. Ducktown, Tennessee, etc.*

* W. H. Weed, *Transactions* American Institute Mining Engineers, Vol. XXX, p. 449; J. F. Kemp, *id.* Vol. XXXI, p. 244.

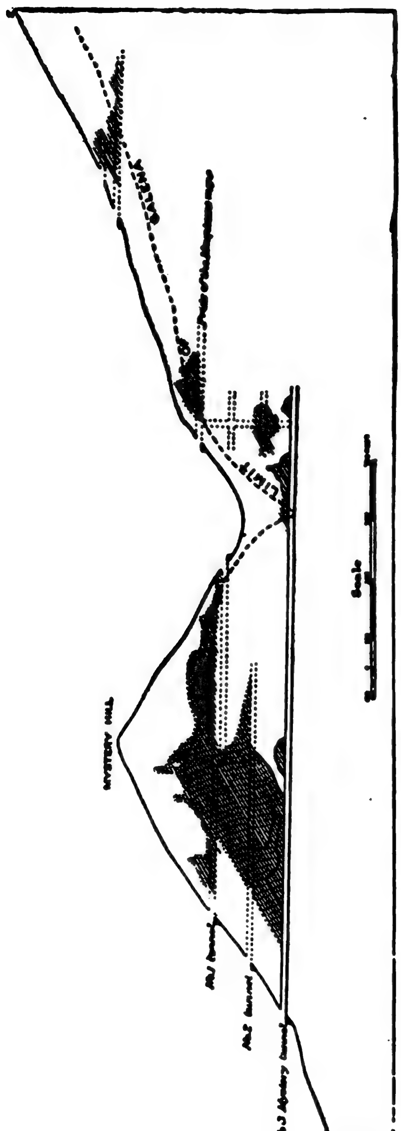

Fig. 67. Close relation of galena zone to surface, an evidence of the work of descending waters. Longitudinal section on Mystery-Pride vein, Monte Cristo, Washington. After J. E. Spurr.

The general conditions permit of a thorough, though not especially deep zone of oxidation, and a high water level, below which sulphides exist.

The solvents or reagents in such surface waters are chiefly (besides the water itself) oxygen and carbonic acid. Iron sulphide, whether free (in the form of pyrite, marcasite, or pyrrhotite), or in combination with copper sulphides as copper pyrite (chalcopyrite) is easily attacked by the oxygen of surface waters, forming iron oxide (limonite), and the sulphur becoming sulphuric acid. Iron sulphate is also formed. The copper sulphide may be transformed into copper oxide in the same way, but it generally goes into solution, chiefly as copper sulphate, and passes downward. On reaching unaltered sulphides, the soluble copper salt is precipitated, forming copper-bearing sulphides, which grow progressively richer with the continuation of the process, the iron being taken away in the form of the soluble sulphate. Pure copper sulphides, like chalcocite (copper glance), is even formed. The iron released by precipitation of the copper sulphide in part finds its way further down in the earth and is there again precipitated, as pyrite.

When this process has gone on for a long time, as it has in this case, where the slopes are gradual and the wearing away does not move faster than the progress of the alteration, there will be a surface zone where the oxidized iron ore (limonite) will be left with the quartz of the original gangue (made spongy by the dissolving out of the original sulphides), with only small amounts of copper carbonates or oxides. This is the characteristic gossan or iron hat. Beneath this will come the secondary zone of very rich copper sulphides, chalcocite and bornite, with pure chalcopyrite. The zone is apt to have considerable extent. It constitutes the principal ore-bearing horizon of many copper mines of the kind described. Beneath, the pure

copper sulphides will disappear, and the proportion of copper in the pyrite will grow less and less, till the original pyrite with a small percentage of copper—the unaltered ore—comes in permanently.

4. Ores of lead, zinc and copper, with silver and gold, in an arid region with slight slopes. Horn Silver mine, Utah.*

This is practically the mineral composition of the Monte Cristo deposits, but the climate and the surface conditions are directly reversed. On theoretical grounds it has already been pointed out that a well-watered country with steep slopes and an arid country with slight slopes were about equally favorable for the concentrating action of downward tending surface waters; and the evidence here seems confirmatory.

The mine is situated at the foot of a mountain, on the edge of a desert valley. The footwall is limestone, the hanging wall, andesite; the gangue is quartz and barite. The workings are down 1,200 feet. Oxidation is only partial; galena outcrops on the surface, mixed with lead and sulphate; yet this zone of partial oxidation extends down to the lowest depths reached.

Going down on the ore-body, changes in the ore occur. The upper ores are lead ores, mainly lead sulphate (anglesite) with sulphide (galena), some carbonates and oxides of lead, and horn and ruby silver (silver chloride and sulphide of silver and antimony). No zinc and copper are found. This class of ore persists down to 400 feet; at 400 and 500 feet more arsenic and antimony are found, and a little zinc. Further down, zinc increases, until at 700 feet there is an enormous amount, generally in the form of carbonate or silicate; a little lead is associated with it.

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* S. F. Emmons, *Transactions* American Institute Mining Engineers, Feb., 1901.

At 650 feet copper begins to come in, and extends down to 750, but not to 800 feet. The ore is largely chalcocite (copper sulphide) with a good deal of galena. The lower levels contain no copper, zinc or lead.

The results are, then, practically the same in these semi-oxidized ores as in the sulphide ores of Monte Cristo, though the mineral zones are somewhat broader. In the Horn Silver mine oxidized minerals and sulphides have evidently been deposited side by side, the small amount of water at any given time permitting this. For example, ruby silver is generally in such cases a secondary mineral, and would normally occupy a deeper zone than the oxidized ores, in districts where the supply of water was abundant and there was a definite and high water level. In the copper belt the sulphide chalcocite is probably secondary, yet it occurs with carbonates and silicates. The mineral zones, therefore, are zones of partial oxidation, to a less degree of secondary sulphide deposition; and a separate belt of secondary sulphide deposition very likely does not exist.

The chlorine abundant in the waters of dry climates shows its effect in the silver chloride. The other reagents were probably oxygen from the air, which converted the lead sulphide into sulphate; carbonic acid, very likely derived from the limestone footwall, which produced the lead and zinc carbonates; and silica, from the solution of the quartz gangue, which produced the zinc silicates.

How deep does the zone of concentration of oxidized or sulphide ores by descending surface waters generally extend?

In the Monte Cristo district, Washington, just cited, a maximum of 600 feet of sulphide enrichment was estimated, and 300 feet is probably a nearer average. In the case of the Horn Silver mine, Utah, the concentrated ores

(mingled oxidized and sulphide ores) extended down to 750 feet. At the De Lamar mine, Nevada, the gangue is quartz, the metallic mineral pyrite and perhaps some form of telluride, and the values gold and silver. The enrichment extends down 700 feet or somewhat more. The ore here is all oxidized.* In the pyrite deposits of southern Spain and Portugal the surface zone rich in copper usually extends some 300 feet down, below which the pyrite contains very little copper.†

At Ducktown, Tennessee, the lower limit of the zone of rich copper minerals, formed by concentration of the original lean magnetic pyrite (pyrrhotite) is about 100 feet below the surface, and the zone is thin, the iron hat or gossan occupying the greater part of this distance. At the Independence mine, Victor, Cripple Creek district, Colorado, the zone of secondary precipitation and enrichment of ores by surface waters extends in general some 400 or 500 feet below the surface.‡

Manner in which Minerals are Precipitated by Descending Waters.

In what forms are metals usually precipitated by shallow descending waters?

Deposits by descending waters may be oxides, sulphates, carbonates, chlorides, sulphides, etc. Those minerals

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* S. F. Emmons, *Transactions* American Institute Mining Engineers, Feb., 1901.

† Klockmann, *Zeitschrift für praktische Geologie*, 1895.

‡ T. A. Rickard, *Engineering and Mining Journal*, Vol. LXXIV, No. 26, p. 850.

which have been affected by the oxidizing process are converted into some compounds containing oxygen, whether it be sulphate, carbonate, or oxide, even if they were originally sulphides.

Copper sulphide in the oxidized zone will be largely converted into copper carbonate (malachite or azurite) or cuprite and tenorite (red and black oxides). Copper sulphate may also be formed, but being soluble in water will not as a rule be precipitated, but will be held in solution until by some reaction the copper is precipitated in another form. But sulphate of lead is relatively insoluble, hence this mineral (anglesite) is frequent in the oxidized zone of lead ores, as well as the carbonates (cerussite) and the oxides (minium, litharge, etc.). Chlorides are formed in the oxidized zone, by the actions of waters containing chlorine or alkaline chlorides in solution, and the metallic chlorides that are relatively insoluble are precipitated. Silver chloride or horn silver (cerargyrite) is a familiar case. Easily soluble chlorides such as those of iron and gold are not found to any great extent.

Under what conditions are ores most likely to be deposited as chlorides, in the oxidized zone?

In arid regions there is little or no free drainage to the ocean, and the surface and ground waters are largely removed by evaporation, leaving their solid compounds behind. Chlorides of sodium (common salt) magnesium, etc., form part of this residue. They have been leached out of the decomposing rocks in small quantities, or

supplied by hot springs, but on continued accumulation and concentration by evaporation become important. Such is the origin of the salt pans and alkali flats, as well as the saline lakes which occupy the depressions of desert regions. In these arid tracts alkaline chlorides are abundant in the shallow underground waters which percolate through the ores, and the results are likely to be chlorination of the metals, the precipitation in the weathered zone of the insoluble chlorides, and a more or less thorough dissolving out of the soluble ones.

Example: In the dry tracts of Arizona, New Mexico and Nevada, where salty incrustations, due to the causes sketched above, are found in nearly every valley depression, the chloride of silver is noticeably abundant and frequent in the weathered zone of ore deposits.*

What causes the deposition of sulphides by descending waters?

Deposition of sulphides from descending waters is often brought about by the reduction of soluble metallic salts by contact with already existing sulphides. For example, a copper solution coming in contact with crystallized pyrite (iron sulphide) may be reduced, so that the sulphide of copper and iron (chalcopyrite) results. Renewed copper solutions acting upon this chalcopyrite may change it into a sulphide richer in copper, such as bornite. Still renewed solutions may change the bornite to chalcocite. Chalcopyrite contains 34.5 per cent. copper, bornite 55.5, and chalcocite 77.8 per cent, so that the quantity of copper is greatly increased.

* R. A. F. Penrose, Jr., *Journal of Geology*, Vol. II, No. 3.

Example: Chalcocite is the principal ore in the great copper district of Butte, Montana, though bornite and enargite are common. The chalcocite forms coatings on the other metallic minerals in such a way as to show that it was one of the latest minerals to crystallize. As depth is gained the percentage of pyrite and enargite increases in comparison with that of chalcocite, so that while the first thousand feet of ores averaged 8 or 10 per cent copper, the second thousand averaged about 6 per cent. The chalcocite has been formed by a chemical reaction between copper sulphate in solution in descending waters and the iron pyrites and other primary sulphides lying below. By imitating the conditions in the mines, chalcocite has been produced artificially.*

What is the action of organic matter in the shallow underground zone, as regards the precipitation of sulphides?

Precipitation by the action of organic matter is very important in the shallow water zone, both near the surface and at considerable depths, and takes place in the same way that has been described for the deeper underground regions. Mine timbers (especially those in old mines) may precipitate metals from solution in mine waters. Dr. Raymond has reported a case in a New Mexican mine, where the eye of an old pick has been filled with galena (sulphide of lead) by the reducing action of the wooden handle which once occupied this position. This is only an example of what must often occur on a large scale when descending solutions come in contact with beds of shale or other sedimentaries containing organic matter. The

* H. V. Winchell, *Bulletin* Geological Society of America, Vol. XIV, pp. 269-276.

reactions are much the same as in the case with ascending solutions. (See p. 246.)

Are metallic minerals deposited by descending waters as replacements or as cavity fillings?

In respect to manner of deposition, the metals borne by the shallow, generally descending, waters, may be precipitated in the same way as those in the deeper waters. Like them, they may be, and perhaps oftenest are, deposited by replacement, preferably of limestone, frequently of some other rock. They may occupy the tiny openings of a porous rock, or cavities formed either by fracturing or dissolution.

CHARACTERISTICS OF ORE-DEPOSITS FORMED BY ASCENDING AND BY DESCENDING WATERS.

Is it of practical value to know whether a given ore-deposit was formed by ascending or descending waters?

This knowledge is often of economic importance.

How can this point be ascertained?

Let us take a case where metalliferous solutions are stopped in their circulation by a relatively impervious stratum, a decomposed dike, or other rock mass, or whatsoever it may be, and where as a consequence of the spreading out and detention of the solutions, ore-deposition takes place. If the ore-deposits are conspicuously placed on the under contact of such an impervious body, it is a fairly safe index of ascending currents; if on the upper side, of descend-

ing. The case is emphasized in folded strata, for the upward-tending solutions will be confined chiefly in the tops of anticlines, and the downward moving ones in the troughs of synclines, and here the ore-deposition will by preference take place.

Example: In the Bendigo goldfield, Australia, described on p. 165, the auriferous quartz veins occur by preference at the apex of anticlinal folds in the stratified beds (saddle reefs) (Fig. 32). Deposits in the synclinal folds (inverted saddles) are rare and unimportant.

Where ore-bodies are formed at an intersection of circulation channels, be those channels joints, faults, porous beds, or any combination of these, they will often be found to form by preference either on the upper or the lower side of such intersections. They will be either in the troughs formed by the two channels converging downward and meeting; or in the roof, formed by the channels converging upward and meeting. The former case is generally an indication of descending waters, the latter of rising ones.

Example: The typical false saddle, auriferous quartz veins of the Bendigo goldfields, Australia, drawn by T. A. Rickard, are, as shown (Fig. 68), formed at the intersection of a joint *a a* with a bedding plane. The fact that the ore-body has formed in the roof rather than in the trough of the intersection may be regarded as indicating that the auriferous quartz was deposited by ascending waters.*

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* *Transactions* American Institute Mining Engineers, Vol. XX, p. 469.

When ore-bodies show constant and evident relation to the surface, being strong on the outcrop, but shallow and becoming impoverished with depth, it is an evidence of formation by descending waters. (See p. 280 and Fig. 67.)

Example: Many iron deposits are examples of this. The Lake Superior iron ore-bodies are due to descending

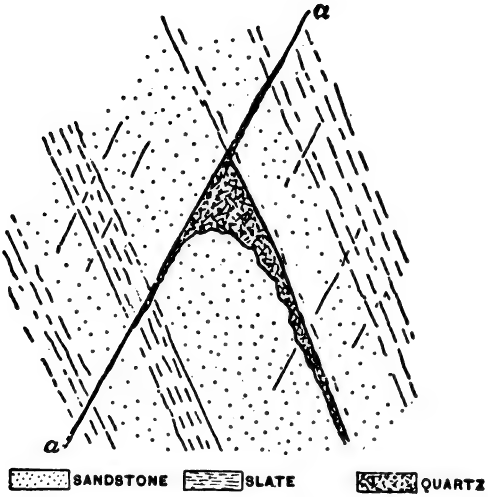

Fig. 68. Ore formed by intersecting fractures. *a a* is fracture cutting across stratification. After T. A. Rickard.

waters, as is shown among other things by their intimate connection with the surface. On the Mesabi iron range, near the north shore of Lake Superior, in Minnesota, great masses of iron ore lie at the surface, under glacial drift (Fig. 69). The iron was originally a marine precipitate, disseminated through a sedimentary rock, from which condition it has been concentrated into commercially

valuable ore-deposits, in favorable places, by descending surface waters.

The presence of cavities crusted with stalactites and stalagmites of ore indicate a downward movement of the waters at the time these stalactites and stalagmites were deposited, and very likely during all the ore-deposition. Since, however, in ore-deposits formed mainly by ascending

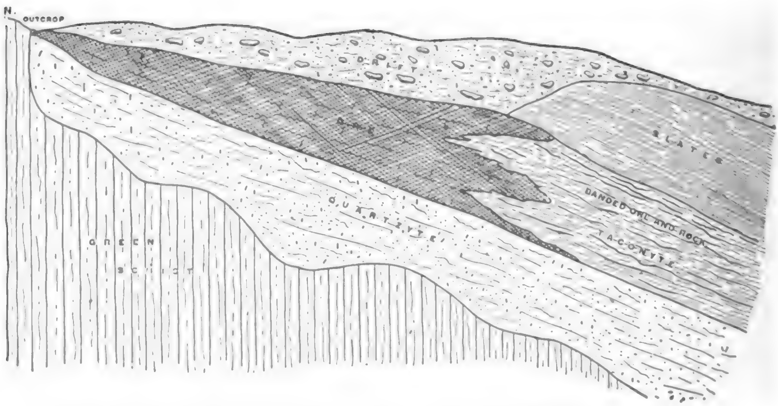

Fig. 69. Iron ore-deposits showing constant relation to surface (formed by descending waters). General section at Biwabik, Mesabi iron range. After H. V. Winchell.*

waters there are apt to be minor stalactitic growths, formed by downward tending surface waters of a later period, short duration, and relatively slight efficiency, one should guard against the sweeping application of this test.

Many ore-deposits are formed by the combined effects of ascending and descending waters, often acting at different

* 20th Annual Report Minnesota Geological and Natural History Survey.

periods. Ore-deposits formed by ascending waters may, as already described, be worked over and redeposited by descending waters. Therefore, one must beware of applying evidence obtained from a single ore-body to all the ores of a district; and one should especially avoid taking the evidence of the shallow ore-deposits near the surface, where there is frequently strong evidence of the work of descending waters, to apply necessarily to deeper ores.

What practical deductions follow the solution of the question as to the deposition by ascending or descending waters?

The efficiency of downward tending waters is greater near the surface, and therefore on going down a moderate distance the ore deposited from such waters is apt to become impoverished and fail rapidly; while a deposit by ascending waters is likely to be much more deep-seated and regular.

CHANGES IN RICHNESS IN DEPTH.

What changes do ores, deposited by descending waters, show in depth?

Ores due primarily to descending waters can be counted on to become poorer in depth, as remarked above. Where an earlier ore-deposit has been worked over and concentrated by descending surface waters, the values will be often less below the enriched shallow zone.

What general changes may ores deposited by ascending waters show in depth?

Concerning the great class of ore-deposits due to ascending waters, it is evident, that, being limited bodies, they will have a top and a bottom somewhere; also that at some point, probably intermediate between the top and the bottom, they will be largest and probably richest. These ore-deposits would ordinarily not be revealed to the eye of man were it not for the removal of the overlying rocks. Therefore, the wholly fortuitous circumstance of the level of the plane of erosion at the time of the discovery of the ore-body determines whether they will become stronger or weaker in depth. Erosion may reveal only the top of a deposit, and it will grow richer below; or it may reveal the bottom, and it will grow rapidly poorer; or it may cut some intermediate level, and the vein may hold its own for a long distance down, with about the same strength and richness. These conditions are apt to be fairly uniform over a considerable district, so far as the ore-deposits formed at a single period are concerned. So in one district the ore characteristically grows weaker in depth, in another stronger.

What changes may sedimentary ores show in depth?

In the case of sedimentary ore-bodies, which have been folded so as to dip at a high angle, it is plain that depth can have no effect in determining richness or poverty.

How deep may a vein extend?

Under favorable circumstances, where there is a strong

water channel, and constant facilities or factors favorable to ore-deposition all along it, it is probable that the resulting vein may extend to a great depth, perhaps in extreme cases, two or three miles below the original surface. Where such a vein is being worked, it may be profitable as far down as the present methods of exploitation can be pushed.

Example: The gold-quartz veins of Nevada City and Grass Valley,* California, show, in general, a continuity down to the greatest depths worked. Many of the smaller veins diminish and disappear in depth; but the larger ones hold their own. In one district there is exposed, by mining and irregularities in the topography, a vertical distance of 3,500 feet, within which there is no evidence of change in the character or quality of the ore; in another place the same truth holds for a vertical distance of 2,600 feet.

These veins must have been formed at a depth of several thousand feet below the surface, and a great part of their original extent (the upper portion) must have been worn away by erosion.

In ore-deposits due to ascending waters, may the character of the minerals change with depth?

There may be a change in the character of mineral in depth, for ores may be deposited according to their relative solubility, by ascending waters, in much the same way (though probably not so regularly and definitely) as by descending waters.

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* W. Lindgren, 17th Annual Report United States Geological Survey, Part II, p. 162.

Example: In the case of the Dolcoath mine in Cornwall, which has probably been formed by ascending waters, copper is relatively more abundant in the upper zone, tin in the lower one.

May ore-deposits formed by ascending waters ever extend great distances downward without change in the character of the ore?

In some cases the character of the ore may remain about the same through a considerable vertical range.

Example: The silver-lead deposits in Aspen, Colorado, show about the same characteristics through a known vertical range of over 3,000 feet. Here the ore-deposition has been largely along a bedding fault. This has usually, on one side, a bed of shales, which have probably contributed toward precipitating the ores as metallic sulphides. The beds are steeply upturned, so that for considerable depths uniform conditions for deposition have obtained.

Is it possible that any veins continue downward indefinitely?

Owing to the pressure exerted by gravity, it is doubtless more difficult for a fissure to stay open in depth than near the surface. The tendency is to press the sides together and close the opening. At a certain depth, it is probably the case that the pressure and the plasticity resulting from this, together with the increase of heat, makes it impossible for fissures, fractures, or other openings to exist. Such depth has been variously estimated at from 16,000 to 33,000 feet.

Is this theoretical downward limit of any practical importance?

This limit is far below the depth that can be attained in mining. But some veins are very old, and even the comparatively recent ones (such as the Tertiary veins) are old enough to have had in many cases several thousand feet of rocks, which overlay them at the time of their formation, removed by erosion. Hence, it is very possible that we may find some veins diminishing and even disappearing in depth.

Why is it that veins may sometimes diminish in size and value below the zone of oxidation?

Near the surface, as already described (p. 182), openings tend to become large and numerous. To be sure of the persistence of a vein which has depended for its origin upon a fissure, or system of fractures, one must first explore it down below the zone of oxidation. Many a vein, large and promising near the outcrop, will be found to dwindle to quite insignificant proportions before arriving at this point; but, if the vein is still strong here, there is good reason for expecting that it may continue so to a good depth, other conditions being favorable.

Is there any relation between the horizontal and the vertical extent of a vein?

There are all kinds of fractures and fissures, little and big, transitory and permanent. It is a saying of some miners that a vein will go down as far in depth as it extends horizontally on the surface in outcrop. This saying seems to

have some sound principle behind it; and practically the same criterion has been applied by W. Lindgren in the case of the gold quartz veins of Grass Valley and Nevada City, California. Mr. Lindgren remarks:* "In considering the probable permanency of a given vein, its general character must be taken into consideration. Continuous well-defined outcrops and wide bodies of quartz are in general good indications of the maintenance in depth, as is also any evidence of strong faulting and movement. . . . A fissure which can be definitely proved to extend only a short distance will in all probability be found to be correspondingly limited in depth."

May a vein change in value in depth, on passing from one rock into another?

In the case where a fissure or fracture system, along which mineralization has taken place, passes from one kind of rock into another, it may change its character so as to influence strongly the character of the vein. For example, a strong fissure in limestone may die out entirely on meeting a bed of shales. This is an influence exerted by the mechanical properties of different rocks.

Where a vein or other ore-deposit depends largely for its existence upon the chemical properties of the rocks through which it passes, the same changes may be expected. For example, a replacement deposit in limestone may be expected to be poor or to stop entirely when followed down into quartzite or granite, although the physical conditions

* 17th Annual Report United States Geological Survey Part II, p. 163.

(the fracture zones and water channels) may be as good in the latter rocks as in the limestones.

In sum, what changes may be expected in depth?

There is, therefore, no general rule as to whether veins and other ore-deposits grow richer or poorer in depth. Sometimes they may grow richer, sometimes poorer; sometimes they may grow richer, then poorer, then richer again; and sometimes the distribution of values may be fairly equable to a considerable depth. Each case must be taken up and investigated separately, before the probabilities can be arrived at.

ASSOCIATIONS OF MINERALS.

Can the presence of a given metal in an ore-deposit ever indicate the probable presence of another?

Owing to chemical affinities (the fact of having similar properties of solution and deposition, etc.) there are associations more or less marked between different minerals in ore-deposits; and this association, once understood, may be of practical advantage to the miner.

What are some of these associations?

Lead and silver are closely associated. Most silver is obtained from argentiferous galena, and most galena contains a greater or smaller amount of silver.

Lead, zinc and iron, most commonly in the form of galena, blende and pyrite, but also in other forms, are intimately associated, and often occur together.

Copper and iron, whether in the common form of chalcopyrite (sulphide of copper and iron) or otherwise, are closely associated. Pyrite may contain a variable amount of copper sulphide, increasing up to the pure chalcopyrite (34.5 per cent copper).

Lead and barium (the latter in the form of barite, or heavy spar) are also frequently associated.

Tin and a number of rare elements are usually associated,

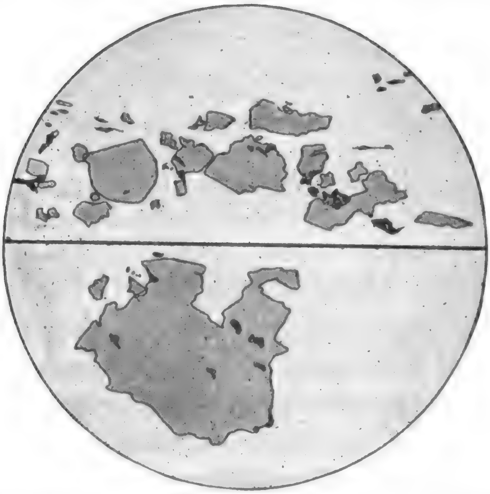

Fig. 70. Thin sections of ore from Omaha mine, Grass Valley, California. Magnified 17 diameters. Light areas, quartz; shaded areas, pyrite; black areas, gold. After W. Lindgren.*

though in any given case (as is, indeed, true for the other associations cited) the combinations may not be found. Among the metals and minerals of commercial value which often occur in company with tin are tourmaline, fluorite, topaz, lithia mica and wolfram.

* 17th Annual Report United States Geological Survey, Part II, Pl. V.

Gold is frequently found in veins of quartz, and is especially associated with iron pyrites in this case (Fig. 70).

Do non-metallic minerals form associations in this way?

Another class of minerals, associated because they are all easily precipitated from evaporating waters, are salt, gypsum, anhydrite, and frequently borax, etc. These minerals often occur also in red rocks, for which the explanation is probably that the oxide of iron which colors the rocks was also a chemical precipitate accompanying evaporation.

The association of organic minerals, such as petroleum, mineral asphalt or bitumen, natural gas and ozocerite (mineral wax), is natural, for these are all the product of the various distilling and other processes operating upon sediments rich in organic mineral. Wherever one of these minerals occurs, others of the same group should be suspected in the region.

ROCK ALTERATIONS AS GUIDE TO THE PROSPECTOR.

What guides do the oxidation processes of veins afford the prospector?

The chemical peculiarities of ore veins and associated rocks may often furnish the prospector a guide to the presence of ore, even where there is little or none in sight. Most oxidized outcrops of veins are marked by a decomposed mass, colored reddish from the oxide of iron which

has been formed by decomposition from the iron present in the unaltered vein. This outcrop may look like anything but a metal vein, but the experienced prospector recognizes the sign, and not only samples and assays the decomposed, often clayey material, but begins making excavations to see what the stuff looks like a little further down. Green stains on such an outcrop may indicate copper, nickel or chromium. Bright blue, green, and red stains together usually mean copper. Bright red stains may come from either lead or copper, or from rarer metals.

Where the outcrop of a quartz vein is cavernous or cellular, and rusty and crumbling, this generally points to the former presence of iron pyrite and other sulphides, which have been dissolved out by the weathering. An assay is then always advisable, for in the dissolution of the metallic sulphides a large part of the contained gold is often left behind, so that this sort of quartz is often very good ore, and it is, besides, free milling. In such quartz the cubic cavities are often exact casts of the dissolved pyrite crystals. In depth these sulphides are reached, and the ore becomes more refractory, the gold which nature has separated in the weathered zone being difficult of separation by metallurgical processes.

What indications of mineralization are afforded by certain rock alterations?

Less well known to the prospectors than the indications afforded by oxidation are those given by the alterations in the wall rocks which often accompany ore-deposits. In

general, if a rock has a thoroughly altered, softened or decomposed appearance, it testifies to the former searching, dissolving and precipitating effect of chemically active solutions, and in so far it is a favorable sign. Rock thus decomposed, whether it was originally granite or quartzite, or anything else, is often called by the general and incorrect term porphyry, especially when in an almost clayey state. An abundance of iron pyrite, in a softened igneous rock, is generally a good sign.

Is this rock alteration always of the same type?

The exact nature of this decomposition and alteration varies, dependent upon the character of the rock thus affected, and upon the chemical nature of the waters which have usually done the work.

Example: The ores of the Silver City and the De Lamar districts, Idaho, occur as quartz veins, carrying frequently high values of gold and silver. The wall rocks in the different mines are granite, basalt and rhyolite. There is good evidence that the veins were deposited by ascending hot waters. The granite has been comparatively little altered by these waters, the basalt more so, the rhyolite intensely. The granite is often nearly fresh close up to the vein, though occasionally it is softened and changed by the alteration of its feldspar to pale yellowish-green, clayey or micaceous products (sericite).

The basalt is altered in a zone along the vein, which, as a rule, is not wide, but of very irregular extent. In the first stages of alteration, it has a dull, earthy, dark-green color, and contains small cubes of pyrite. When further

altered, the rock becomes bluish-green or yellowish (due to the development of the mineral epidote).

The rhyolites are the most altered of all, the rocks for many hundreds of feet from the veins being changed. The chief process has been silicification, so that the rock often keeps its hardness and has a deceptively fresh appearance. It sometimes contains also pyrite, for example, at the De Lamar mines, where this mineral is very abundant. Sometimes the rock has been softened, and near the veins some streaks have been entirely converted to white or yellowish clay (kaolin).*

How are rocks altered near tin veins?

In the neighborhood of tin veins in granite (the usual occurrence) the rock is changed, largely by the removal of its feldspar, and the deposition of some new minerals, especially white mica (muscovite), in its place, to a rock called "greisen." This preserves a granitic appearance, but is made up essentially of quartz and muscovite.

What does the silicification of rocks signify?

The alteration of rocks (preferably limestones, although to a less extent other rocks) to silica is a favorable sign. The resulting rock is jasperoid. Miners call it quartz, quartz-rock, flint, chert, hornstone, jasper, etc. Ore-bearing solutions generally contain a large amount of silica, and where ores are deposited (and often where they are not) this silica replaces the country rock in the neighborhood of water channels. Ore-deposits are not in-

* W. Lindgren, 20th Annual Report United States Geological Survey, Part III, pp. 124, 177.

frequently surrounded by a sort of rough shell of such jasperoid.

Example: In the Tintic silver-lead-copper mining district, Utah, (described by Tower and Smith)* the most common form of chemical alteration is the substitution of silica for lime, which when complete, forms jasperoid. In this change the structure, texture, and color of the original limestone are usually retained. The jasperoid is not only intimately associated with the ores, but forms large bodies which have little or no metallic content.

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* 19th Annual Report United States Geological Survey, Part III.

CHAPTER VI.

THE RELATION OF PHYSIOGRAPHY TO MINING.

What is physiography?

Physiography is a study of the features of the earth's surface and the causes by which they were made to assume their present shape. By this study we arrive at the comprehension of the processes by which mountains, hills, valleys, lake basins, etc., were formed. These processes include movements of the earth's crust, both faults and folds, and the erosion of rivers, glaciers, seas, lakes, etc. The application of physiography to mining is perhaps of limited extent, but often appears unexpectedly.

Which are more favorable to ore-deposits, mountains or plains?

In general, mountains are more favorable to ore-deposits than are plains, because mountains are regions of disturbance. Here the rocks are usually folded, igneous rocks are likely to occur, faults and fractures are developed by the movements, and all conditions necessary to ore-deposition may be present.

In plains, on the other hand, the rocks are more likely tc be undisturbed, and igneous rocks and fracture zones are less likely to occur.

In mountainous regions, also, the underground water circulation is generally more vigorous, on account of the greater differences in elevation. Water sinking into the rocks at the top of a steep mountain, for example, and emerging at the foot, will circulate vigorously through the intervening space. In flat countries this element is practically absent.

Are ore-deposits ever found in plains?

Some plains are the roots of old mountains, smoothed out and leveled by continuous and persistent erosion; and in such places one may find the ore-deposits that were formed in the old mountains. This is especially likely in the case of such veins as were originally deposited at a considerable depth below the surface, such as gold quartz veins and tin veins.

Moreover, it is possible, even in flat-lying rocks, that the condition of circulation, the supplies of disseminated metals, and the conditions for deposition, may be so favorable as to determine the formation of ore-bodies.

What is a fault topography, and why may it sometimes serve as a guide to ore-deposits?

There is in each district a distinct type of topography, determined by the natural distribution, relative hardness, etc., of the stratified and igneous formations which make up the rock mass. Faults have a peculiar effect, in breaking in upon this type of topography with irregularities, which are partly due to unequal erosion caused by lines of weakness developed along fault zones, and partly to the unequal

erosion produced by the checkering of rocks of different degrees of resistance, by the faulting. If the faulting be complex (especially if there be two or more systems of intersecting faults), it may produce a very irregular minor topography, often marked by low rounded hills, and very striking to the eye of the trained geologist, as deviating from the conventional type. Such districts, especially if they are in a region where igneous rocks occur, are frequently favorable for ore-deposits. The areas of complex faulting may often be regarded as the outcrop of a sort of rock column, where the openings are so large as to induce a concentration of the water circulation. The mining camps of Leadville and Aspen, in Colorado, and Pioche and Eureka, in Nevada, are good examples of this kind.

Single faults are also frequently connected with ore-deposition, and may be traced from the topography. A cliff or scarp may result from the direct dislocation of the surface by a fault, or from the unequal erosion of rocks brought together by it. In other cases the fault is marked by a gully or valley.

Do veins ever produce characteristic forms in the topography?

Sometimes veins are harder than the rocks in which they occur, and in this case erosion leaves them as ridges of an unmistakable nature. Such is often the case with quartz veins and other hard veins. On the other hand, a vein may wear away, when exposed to the weather, more rapidly than the rock, and then is marked by a straight groove in the surface.

Examples: 1. In the Bendigo gold quartz region, Australia, the quartz veins are more resistant to erosion than the enclosing Silurian slates and sandstones, and hence, are left at the surface as projecting ridges or ledges.*

2. In the region around the Copper Queen mine, Arizona, a relation can be traced between the surface of the ground and the underlying ore-bodies. The ore-bodies, having been eroded faster than the enclosed rocks, form well-marked depressions.†

When may a knowledge of the characteristic erosion forms of different kinds of rock aid in locating ore-deposits?

Where a given rock in a district is known to be preferably selected for ore-deposition this rock may often be recognized by the peculiar topography of the country. For example, a limestone weathers quite differently from a quartzite and produces a distinct topography; a shale or slate is again different. Eruptive rocks may generally be distinguished from sedimentary by the difference in the topographic forms produced.

How are deposits of soluble minerals sometimes indicated in the topography?

In the case of stratified soluble minerals, especially rock salt, the dissolving out of portions of the salt bodies underground by circulating waters often causes a series of depressions or sinks along or near the line of outcrop, by

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* T. A. Rickard, *Transactions* American Institute Mining Engineers, Vol. XX, p. 318.

† James Douglas, *Transactions* American Institute Mining Engineers, Vol. XXIX, p. 537.

which the salt zone may be recognized. Such sinks exist in the neighborhood of the great salt deposits of Stassfurt, in Germany, and the settling of the rock due to the underground caverns has often involved the partial ruin of villages.

Are ore-deposits more likely to occur at the tops of hills or at their bases?

Professor Van Hise* has explained that in regions where deposits were made by descending waters during the existence of the present topography ore-deposition is likely to be greater at the crests, or beneath the upper slopes, where the quantity of descending water is greatest. Deposits by ascending waters, he explains (always restricting this observation to such ore-deposits as were formed during the present topography) are more likely to occur beneath the valleys, or beneath the lower slopes, for here ascending springs usually emerge. Third, ore-deposits which have been first formed by ascending waters and subsequently enriched by descending waters will be on the slopes, probably in many cases nearer the valleys than the crests.

* *Transactions* American Institute Mining Engineers, Vol. XXX, p. 27 *et. seq.*

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